5G Architecture 2017

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Mobile Experts

5G Architecture 2017: Radio Implementation Details

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MOBILE EXPERTS

5G ARCHITECTURE 2017:
Radio Implementation Details

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Cover photo courtesy of Kathrein-Werke

1 EXECUTIVE SUMMARY

The market for 5G is now starting to become more clear. Over the past three years, we've followed the development of Fixed Broadband business cases and IoT applications, and frankly neither of these areas have been very compelling. The mm-wave fixed-broadband case only has fit a highly targeted market in North America, and IoT applications are well served by other cheaper alternatives.

Now, spectrum at 3.5 GHz and 4.5 GHz is coming to mobile operators in China and Japan, where high mobile traffic density justifies another intense deployment of infrastructure. Operators in dense Asian cities will be deploying large numbers of radio heads for 5G, using these sub-6 GHz bands to achieve the broad coverage required in a mobile network.

Millimeter-wave 5G will be a secondary part of the overall 5G picture in the end. Five years from now, we will recognize the "primary" 5G bands at 2-6 GHz, since these bands will achieve the coverage required for widespread service. However, because the lower frequency bands have limited RF bandwidth, mm-wave bands will be added for capacity. Bandwidth of 500 MHz or more can only be found higher than about 24 GHz. Propagation is challenging in these bands, so we can think of the mm-wave 5G link as a Carrier Aggregation layer.

Over the years, each generation of mobile technology has taken two major steps. With 2G, coverage was established at 900 MHz, then more capacity was added at 1800 MHz. In 3G, coverage was set with a macro deployment, and then HSPA upgrades added capacity. LTE started with a macro deployment and then small cells and CRAN followed. In 5G, we expect the 3.5 GHz and 4.5 GHz deployments to represent the "macro" deployment, and mm-wave radios will fill in capacity.

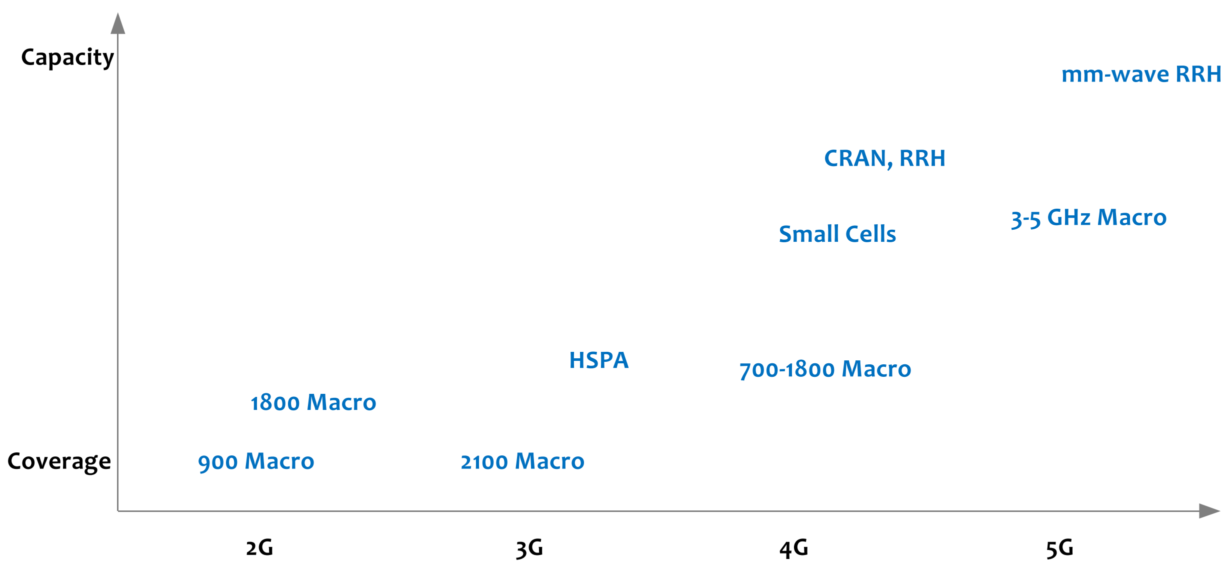

Figure 1 5G RAN Big-Picture Overview

Source: Mobile Experts

At a high level, cost reduction is the real story behind 5G. We already can access the Internet and connect our devices over LTE, but the cost of streaming video is too high for mobile operators to be competitive in the entertainment market. Mobile operators want to become the primary venue for watching video programming and movies. They need a low-cost method for delivery.

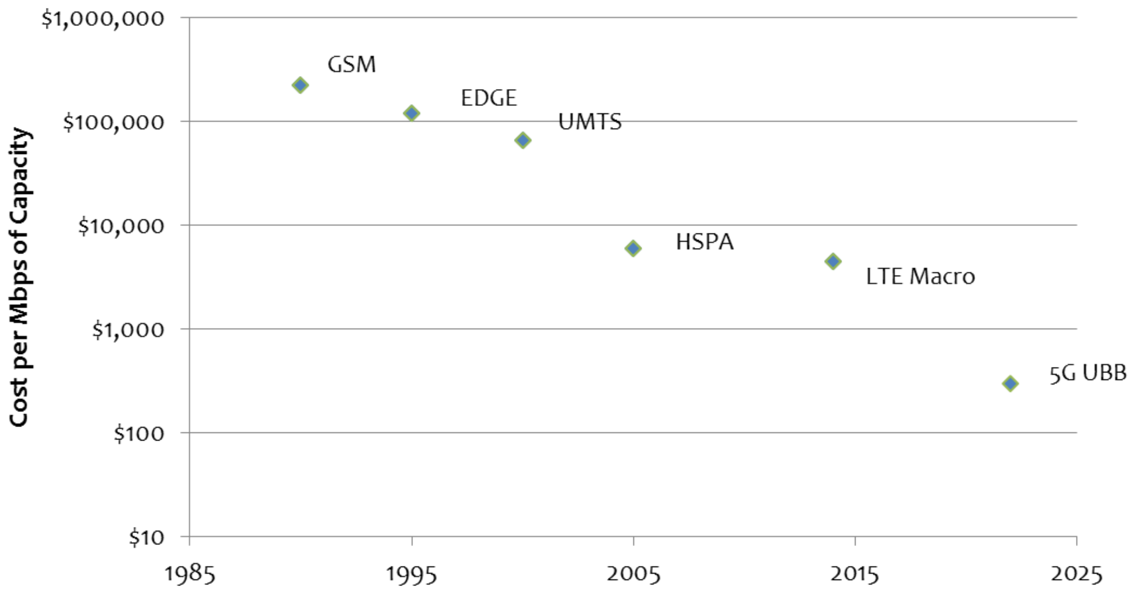

Chart 1: Cost Evolution, 2G to 5G

Source: Mobile Experts

Note: Total Cost of Ownership shown (CAPEX plus 8 years of OPEX)

In the past, Mobile Experts has been cautious about releasing a strong forecast for 5G. We now see multiple signs that 5G can find a successful business case, so we're opening up our forecast to include some significant deployment in Asia. We believe that other world regions will lag behind, making the 5G investment cycle slower than the rapid surge seen in LTE deployment worldwide. Overall, 5G will be a significant wave of business that will begin with fixed-broadband CPEs, then move to tablets and hotspots, and finally will land in smartphones.

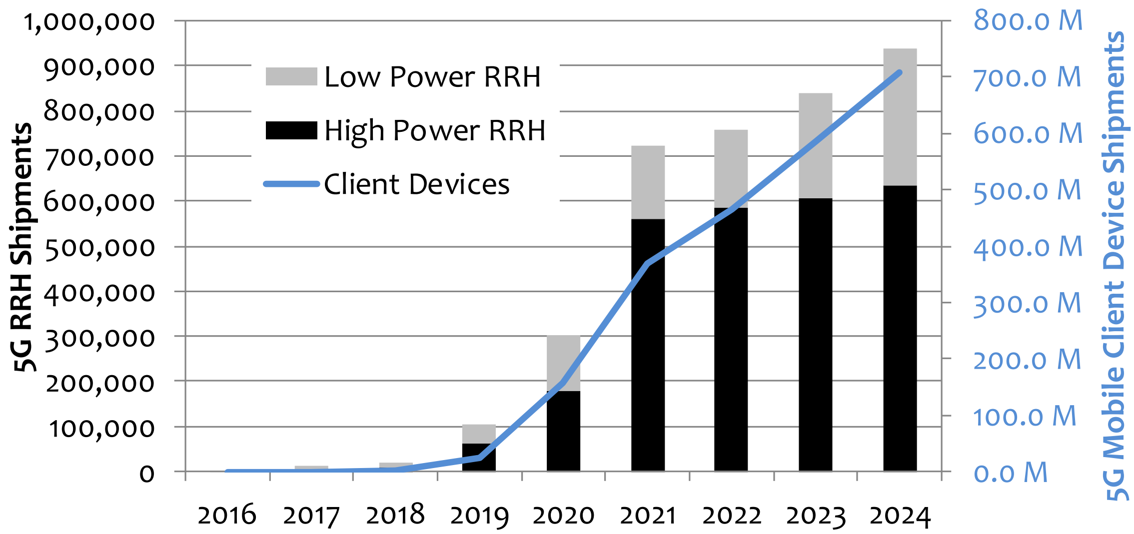

Chart 2: 5G Forecast, RRH Sectors and Client Devices

Source: Mobile Experts

2 TECHNOLOGY BACKGROUND

This year, the technology for "5G" has moved from a nearly random list of crazy ideas to a shorter list of specific items that have support in 3GPP committees and other organizations. Of course, nothing is set in stone yet because the standards have not been ratified. However, we can now identify some specific features of 5G that have strong consensus.

Standards Status

At a high level, the simple story is that the standards are still in the "study" phase. A few key items have been settled quickly, such as establishing a channel model in new frequency bands—because other development depends on a common channel model as a reference. Otherwise, everything is in a non-binding "study item" within 3GPP.

Multiple 3GPP committees are collaborating to work out the very complex workings of the NR waveform, multiple access schemes, and hundreds of other factors that define the NR format itself.

- Within 3GPP, RAN1 is expected to close a study item within Release 14 (during March 2017), which settles the open study phase and begins the "work item" as a part of Release 15. The study item (designated TR38.912) contains multiple documents, including:
    - 38.801 studies NR Access Architecture
    - 38.802 studies the PHY
    - 38.803 looks at RF coexistence (in RAN4)
    - 38.804 handles details of the radio interface protocol
    - 38.900 defines the channel model
    - 38.913 defines overall scope and scenarios for 5G
- The RAN4 committee is working in parallel with RAN1, to define more practical aspects of the radio implementation, including evaluation of real-world hardware to hopefully define achievable specifications.
    - TR38.803 is the study item for NR radio access technology
    - Several other items have been documented in RAN4, including TR37.840 as a study of RF requirements for active array systems, and others
    - Notably, the radio features defined in RAN4 can often be implemented in multiple air interface standards, so as an example active antenna arrays with MU-MIMO are now deployed in TD-LTE systems.

The overall timeline for 3GPP standardization is moving along. Release 14 study items are coming to a close, and specific work items are about to begin. This transition means that open "blue sky" discussion comes to a close, and the focus of the organization will be on hammering out the details of a working specification.

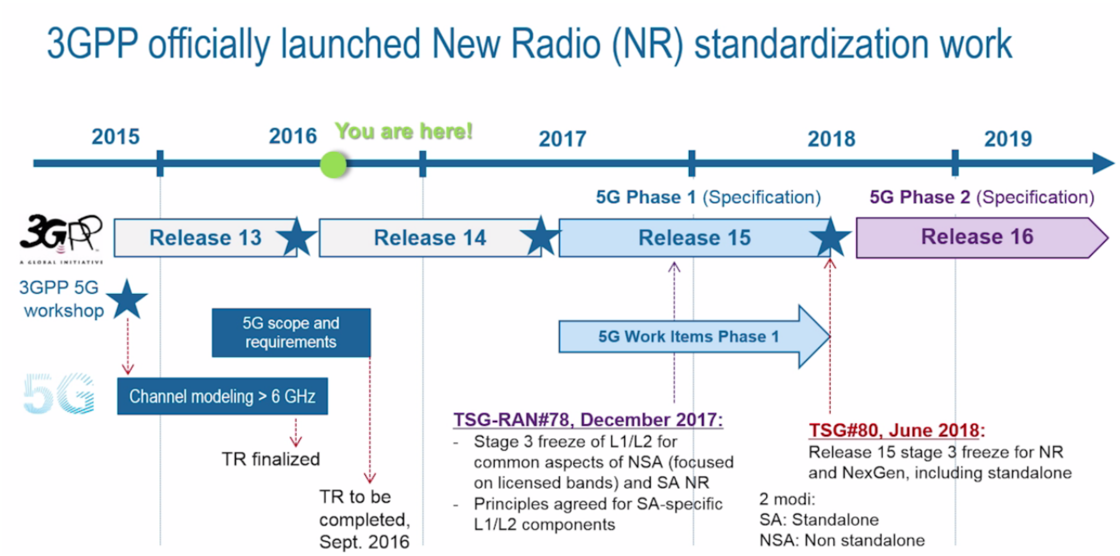

Figure 2   5G Standardization Timeline

Source: 3GPP

The goal for 3GPP is to freeze the PHY and MAC by the RAN#78 meeting in Lisbon, during December 2017.   This initial "freeze" will apply to Non-Standalone (NSA) networks, which refers to the initial 5G networks which rely on LTE control signals for high-quality signaling.   During the same meeting, the group has discussed "principles" for stand-alone networks.   Based on the level of activity happening now, clearly there is much higher focus on NSA networks, and the SA variation will get only cursory treatment this year.

The current timeline calls for a freeze of all "Phase 1" 5G work items by the June 2018 meeting, to be held in the USA in June 2018.   A few operators are pushing to accelerate the overall freeze of "Phase 1" to the December 2017 meeting, but that move seems unlikely right now. The June 2018 milestone would ideally apply to both NSA and SA networks, culminating in Release 15 specifications.

Phase 2 activities are targeted to upgrade 5G networks to meet the expectations of the ITU in their IMT-2020 goals, with release in late 2019.   From a commercial point of view, the ITU specification is arbitrary, so these improvements will be implemented on a case-by-case basis.

Note that, in addition to all of the RAN1 and RAN4 activity on NR, 3GPP has parallel activities related to "Next Generation Architecture", which are more focused on the overall system approach to core networks and mobile networks.

Technology Consensus: Decisions that are likely to win

As we stated before, none of the 5G NR specifications are etched in stone, because study items are non-binding and the main work items have not yet begun.   Having said that, clearly the industry has settled on key features of 5G which are certain to be ratified.

1. Massive MIMO: Also known as full-dimension MIMO, FD-MIMO, or 3D-MIMO, the use of more than 8 antenna elements per sector allows for a dramatic increase in spectral efficiency, because the spectrum can be re-used effectively by breaking the sector into narrow beams.
2. OFDM with Options: In the New Radio frame structure, the number of subcarriers, bandwidth, and subcarrier spacings are all expected to be flexible. Cyclic prefixes are likely to be optional, with filtering either at the subcarrier level or in groups of subcarriers. Overall, the intention is to modify OFDM to improve out-of-band spurious emissions, keep Peak-to-Average Ratio (PAR) as low as possible, and allow for very flexible use of spectrum, from ultra-reliable low latency communications to very high throughput links.
3. Dual Band 5G Networks: Mobile operators that have plans to deploy 5G networks in the mm-wave frequency bands have conducted numerous trials, and universally have concluded that 5G requires either LTE as a control plane, or an additional spectrum allocation below 6 GHz for control signaling. The propagation above 24 GHz is too poor to guarantee a continuous control channel. Stand-alone 5G Broadband networks are likely to use a low band for coverage and control plane, with aggregation on a mm-wave band for high capacity.

Massive MIMO (M-MIMO, FD-MIMO, 3D-MIMO)

The best way to think of this: Massive MIMO is a way to convert a typical 3-sector site to a 12-sector or 24-sector site, using narrow antenna beams…and this can increase the theoretical spectral efficiency from 2bps/Hz to 8 or 16 bps/Hz. In practice, the spectral efficiency gain is lower when users are clumped closely together, due to the limitations of beamwidth in real-world antennas.

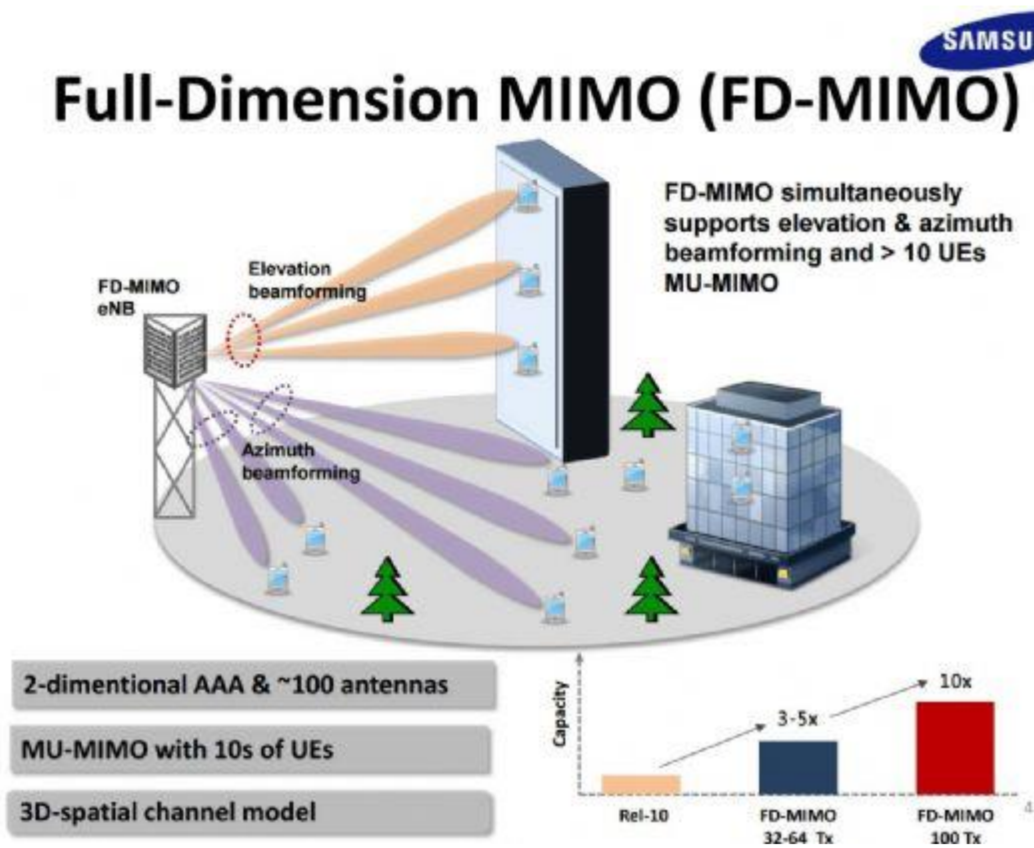

Figure 3 FD-MIMO Illustration

Source: Samsung

To function effectively, Massive MIMO includes multiple aspects:

- An Active Antenna System, with beamforming using multiple antenna elements. In general, the number of elements must be 4X the number of beams actually employed, in order to get effective separation between beams.
- Integrated Antenna Radio (IAR) implementation. Especially at mm-wave bands, the integration of the RF components and the antenna elements (without wirebonds and microstrip traces on a PCB) can be critical to reducing loss. Without tight integration between the antenna and the RF front end, the mm-wave array would be ineffective. The rest of the RRH (ASIC or FPGA) might be located elsewhere, but most OEMs (if not all) will use full integration of the RRH and antenna.
- MU-MIMO. A typical 5G array is likely to use 64T/64R radios in a 64-element array or higher, resulting in as many as 16 MIMO streams. Multi-User MIMO allows these data streams to be allocated to users in flexible configurations…in a simple example, four users can enjoy 4x4 MIMO, or eight users can get 2x2 MIMO.

OFDM….with options: FBMC (FB-OFDM), UFMC, GFDM, f-OFDM

LTE is based on Orthogonal Frequency Division Multiplexing, and achieves fairly high spectral efficiency. Participants in the 3GPP process all seem to recognize that OFDM is a good basis for a 5G NR waveform, but many players have different ideas about how to modify OFDM.

- Should a Cyclic Prefix be used to reduce intersymbol interference, and allow linear convolution for channel estimation? In general, the answer is yes, but the remaining question is the length of the cyclic prefix.
- How can filtering be used to reduce out-of-band emissions? FBMC applies a filter to each subcarrier, while UFMC filters blocks of subcarriers in a given band. Filtered OFDM (f-OFDM) filters sub-bands as well.
- How long should the filter group delay be, compared with the cyclic prefix and the symbol length? This question can impact the level of out-of-band emissions and the overall spectral efficiency (based on orthogonality of different users)

Waveform	Filter type	Filter Length	Time Orthogonality	Freq Orthogonality	OOBE
OFDM	Whole Band	< CP	Orhogonal	Orthogonal	Poor
FBMC	Subcarriers	>Symbol Duration	Othogonal in real domain	Orthogonal in real domain	Very good
UFMC	Sub-bands	= CP	Orthogonal	Quasi-orthogonal	Good
GFDM	Subcarriers	>>Symbol length	Non-orthogonal	Non-orthogonal	Good
f-OFDM	Sub-bands	< Symbol/2	Non-orthogonal	Quasi-orthogonal	Very good

Figure 4 Detailed comparison of OFDM, FBMC, UFMC, GFDM, f-OFDM

Source: Huawei, Mobile Experts

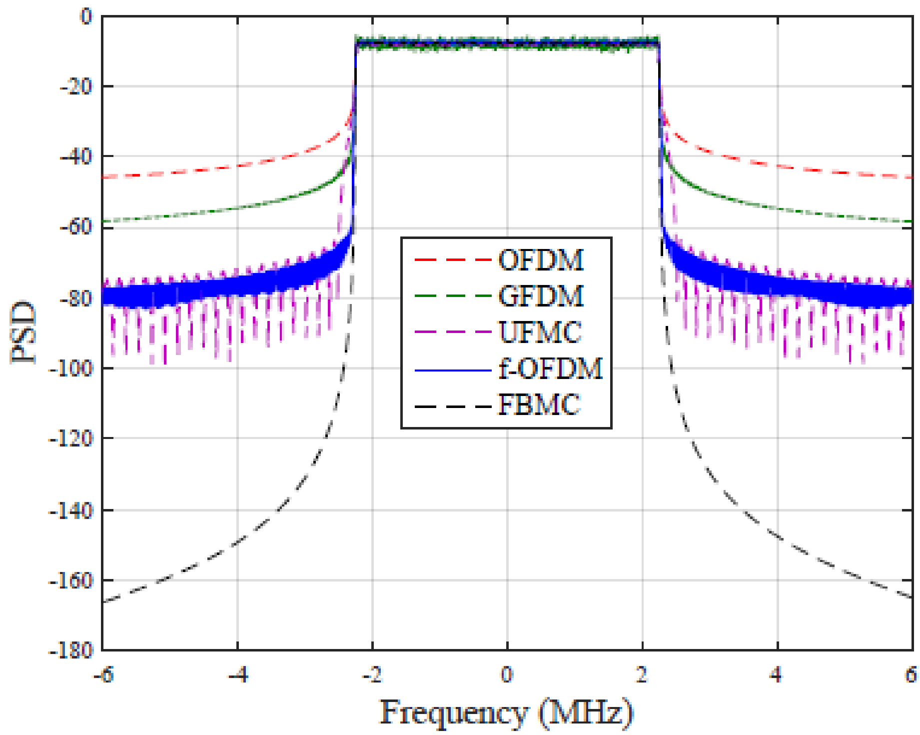

Figure 5 Out-of-band emissions simulation for OFDM, GFDM, UFMC, f-OFDM, FBMC

Source: Huawei

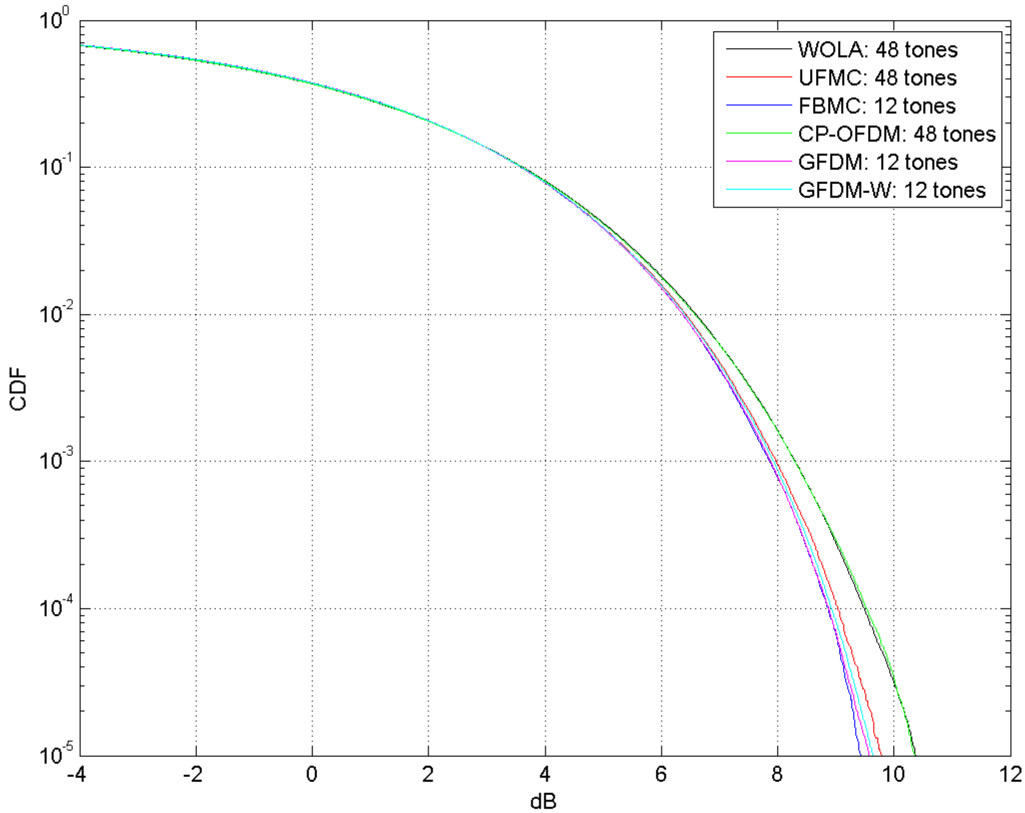

Figure 6   Peak-to-Average Ratio for OFDM, GFDM, UFMC, f-OFDM, FBMC

Source: Qualcomm/3GPP

At this point in time, it's not clear which of these variations will win, as the basic concept behind 5G broadband links.   GFDM can require high order filters and complex processing. FBMC's long filters can create problems in a beamforming scenario. UFMC can experience high out-of-band emissions when heavily loaded with traffic.   Currently, f-OFDM seems to be a good compromise of multiple factors, but we will need to wait another year to see which specific implementation is chosen.   The main point here is that with all of the tradeoffs considered, the broadband application is very likely to settle on a variation of OFDM.

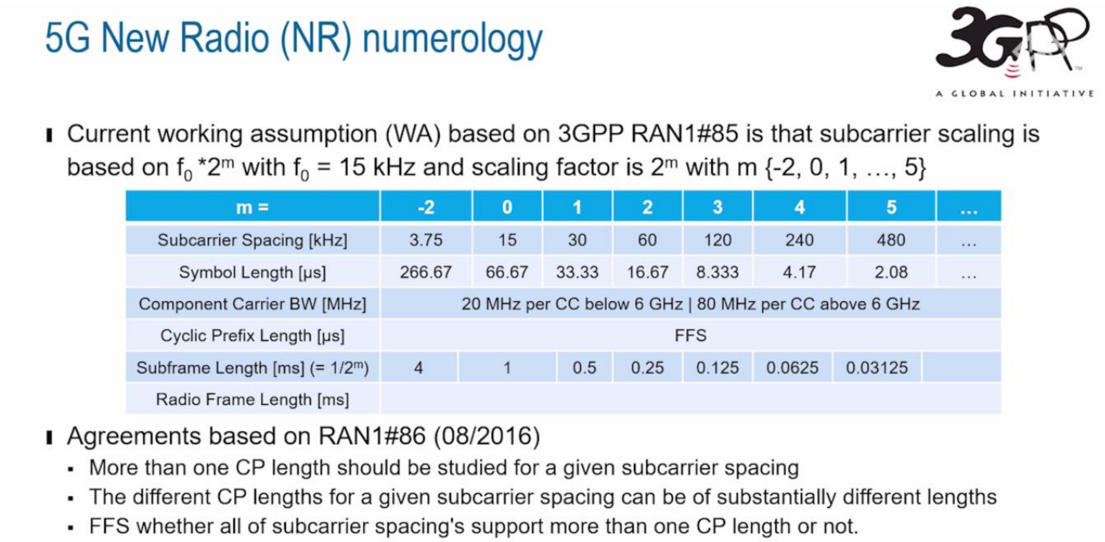

Figure 7 Current working consensus for 5G NR numerology, subcarrier spacing, CP options

Source: 3GPP

Dual Band Networks—migration from NSA to SA

Initial mm-wave 5G networks will rely heavily on LTE core networks and LTE control channels at 1-2 GHz. Propagation of 28 GHz and 39 GHz has multiple aspects which will prevent its use for the control plane:

- Diffraction of signals around obstacles is dependent on the wavelength of the radio wave. At mm-wave frequencies, diffraction around a large building is negligible.
- Reflection of radio waves at mm-wave bands is still possible, but remains highly directional. Several trials have been conducted to show that in an urban environment, non line of sight (NLOS) links can be established using reflections. The reflective properties of glass, concrete, and other building materials will make reflections unreliable for control path signals.
- Penetration of building materials is poor above 10 GHz, including glass, wood, brick, concrete, and other major building materials. A glass window can range from 6 dB attenuation (single pane, low angle, no metallization or tinting) to 40+ dB (metalized glass, dual panes, high angle). This factor may be the most important reason that mm-wave signals are not considered viable for the control path.
- For handheld devices, the attenuation caused by the user's hand can be very significant above 24 GHz. Even with a line of sight to the base station antenna, the user can defeat the link simply by holding the smartphone in his hand.

For all of these reasons, initial 5G deployment is all planned using Non Stand Alone configurations, using LTE control planes and aggregating data on the 5G link. The impact on capacity in the 4G network is unknown at this time, but it's possible that the control plane traffic for a mobile 5G network will have a significant impact on capacity for LTE.

As a result, we can expect operators with requirements for highly mobile capacity to move toward Stand-Alone (SA) networks in the 2020-2022 timeframe. The RF propagation challenges associated with mm-wave bands will not change (laws of physics!), so these operators will pursue 5G frequency bands below 6 GHz as a coverage layer, to replace the LTE control plane.

Because wide spectrum blocks are not available anywhere below 6 GHz, mobile operators are only likely to get smaller slices of spectrum. In Japan, the 4.5 to 4.8 GHz band will be set aside for 5G, with each major operator receiving a 100 MHz slice. This is not enough spectrum to achieve the operator's goals for capacity, but it's enough for control plane traffic and capacity for fast-moving users. More stationary users would rely on the 4.5 GHz control plane and a mm-wave link for higher capacity.

In China, a similar scenario will play out with 3.5 GHz designated as the likely 5G coverage band. Other countries are likely to follow, either re-farming existing LTE spectrum or setting aside new spectrum in the 3-5 GHz range.

Other Technologies: Ideas that might be included

While some technologies have universal support, other ideas have been suggested which have limited support from only one or two players. Thirty years ago, a standards organization would have pushed these "fringe" ideas off the table, because a "standard" meant that all implementations should be the same. Nowadays, however, 3GPP allows a great deal of flexibility in the standards, with options to implement variations of many kinds. Here are some ideas that might be included as options:

NOMA: Non-Orthogonal Multiple Access

This approach, supported by NTT DoCoMo, applies interference cancellation so that two users can share the same spectrum at different power levels. DoCoMo's simulations show an incremental improvement over OFDMA, in the range of 29% for average users and for cell-edge users. More testing will be required to understand how well this can work in a crowded interference environment.

SCMA: Sparse Code Multiple Access

SCMA represents a technique for reducing complexity in the encoding compared to OFDMA, directly mapping incoming bits against a multi-dimensional codebook. In theory this approach improves spectral efficiency and range.

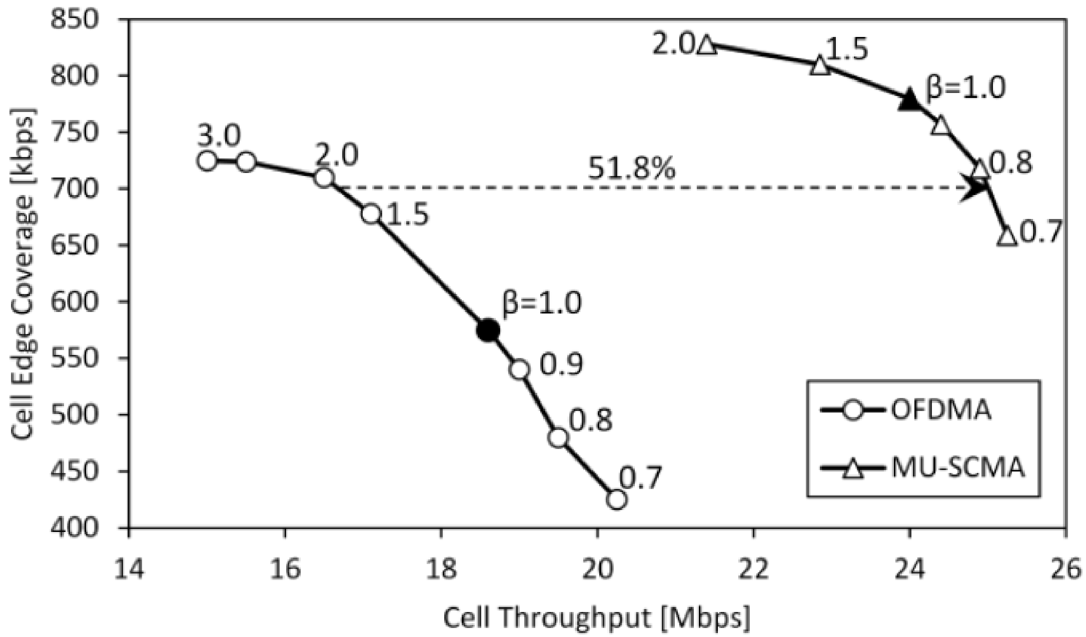

Figure 8. SCMA vs OFDMA Simulated Performance

Source: Huawei

Network Slicing

NGMN has proposed the concept of network "slices" as a concept for handling software development on the 5G network. In short, the overall 5G network will have a "slice" for smartphone and CPE users, another "slice" for Massive MTC users, and additional "slices" for each additional major application. The NGMN concept calls for shared schedulers and separation of the control plane from the user plane, so that network resources can be effectively shared between multiple slices.

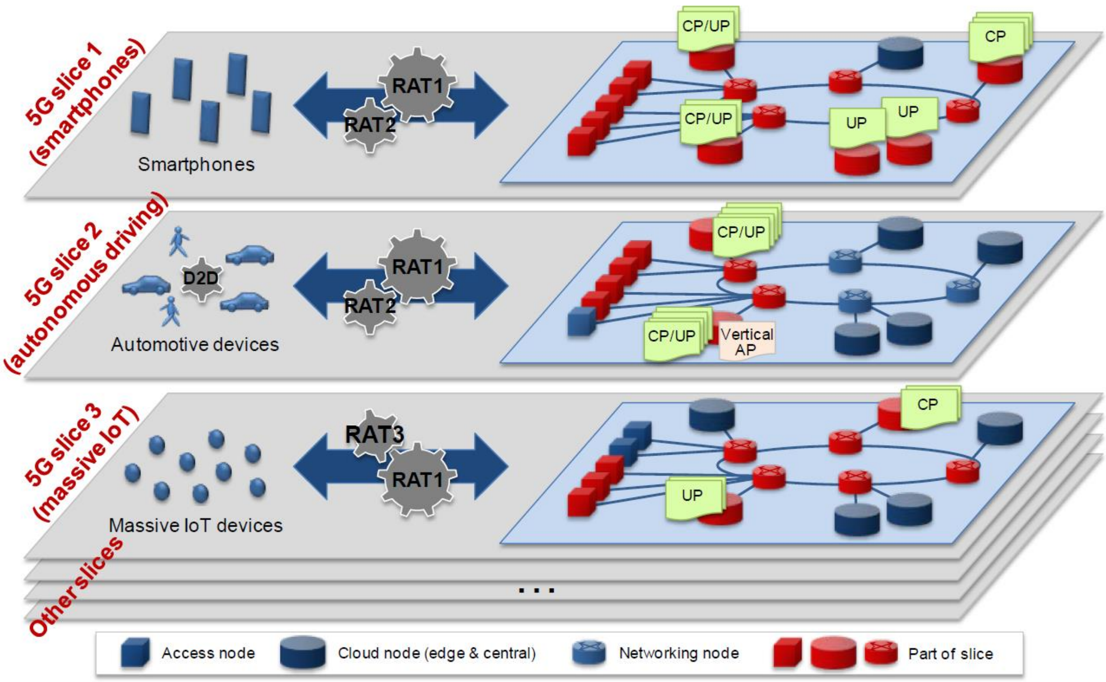

Figure 9. 5G Conceptual Diagram—NGMN

Source: NGMN

This approach of using "slices" has been settled by industry consensus, so this will be at the heart of the 5G concept. "Slices" mean that the virtualized core network and the virtualized baseband processing must be flexible enough to instantly switch from high-throughput mode to bursty MTC mode. In addition, Wi-Fi, LTE or even 2G/3G radios must be prepared to aggregate with dedicated 5G radios, to supplement coverage or aggregate additional bandwidth.

To achieve 5-10 Gbps data throughput in a wireless link, the 5G system will break away from the 450 MHz-2.7 GHz frequency bands used in 2G/3G/4G. In this case, the 5G system will employ frequency bands somewhere above 20 GHz, as well as changes to the air interface in terms of higher order MIMO. The basic underlying principle of OFDM will be used, but with wider bandwidth the specific implementation will be modified to deliver extremely high throughput.

As a result, the radio portion of the network will include entirely new radio heads and baseband processing. In our diagram, we show a remote radio head which includes a portion of the PHY and MAC baseband processing, to keep the bandwidth requirements on the backhaul/fronthaul to a minimum. In addition, the centralized baseband processing pool has been virtualized, so when 5G arrives the baseband resources can be scaled up as needed to handle the extra load.

Software Defined Air Interface

In addition to the pending question about the basic multiple access scheme (which variation on OFDM), the air interface includes other options. Every major OEM is currently considering "flexible radio" or "Software defined air interface" architectures in which the choice of modulation, coding, and multiple access approach can be altered on the fly.

Multiple elements make up the overall "Air Interface", including the coding, the multiple access scheme, and the spatial processing. In 5G, we can expect options to arise in all three of these areas:

1. Channel Coding & Modulation: Here, approaches range from higher order QAM (256QAM and even higher) to WAM, FQAM, and adaptive coding/modulation schemes.
2. Multiple Access Formats: OFDMA is the baseline, but variations such as SCMA and non-orthogonal schemes can increase efficiency.
3. Waveforms: Alternative filtering and cyclic prefix schemes can improve interference immunity and efficiency over LTE.
4. Spatial Processing: Distributed MIMO and Massive MIMO offer big benefits in spectral efficiency.

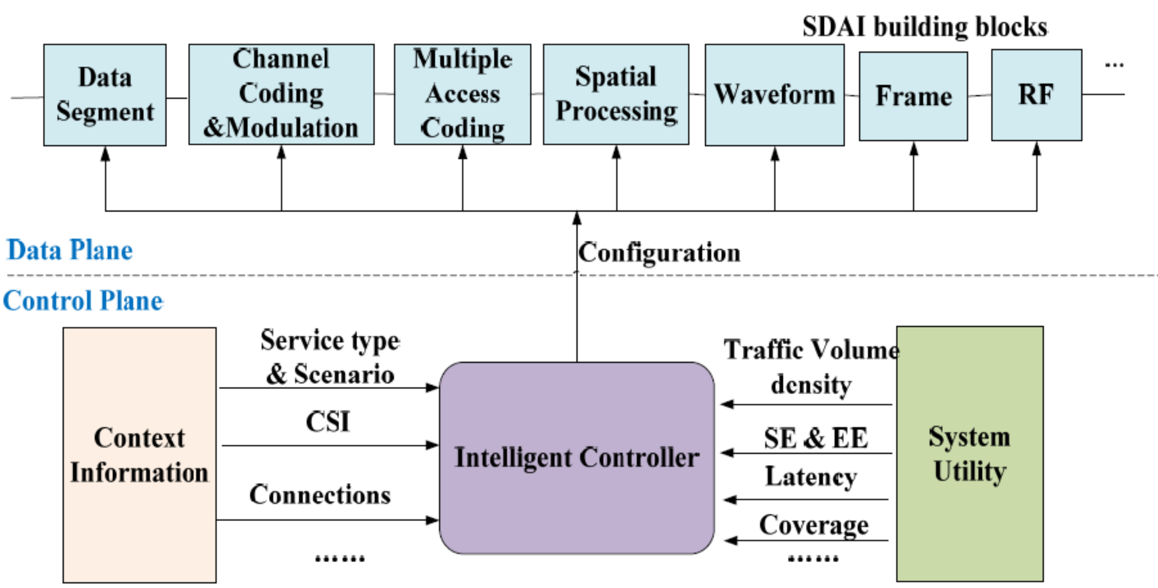

Figure 10 Software Defined Air Interface Concept

Source: China Mobile

Alternative Modulation

The LTE standards have an ever-widening set of options, ranging from QPSK to 64QAM and 128QAM for LTE-Advanced. New alternatives are proposed both on the high end and for the low end to improve efficiency.

WAM Modulation

HSPA+ and LTE use modulation up to 64QAM, and LTE-Advanced currently has a roadmap extending to 128QAM. In 5G, the industry could decide to extend QAM modulation farther, to 256QAM or higher. Higher order modulation requires higher signal-to-noise ratio to provide an advantage,

Another possibility will be to move away from QAM, to use a different modulation approach entirely. MagnaCom has proposed a technique that they call WAM, which may hold an advantage over high-order QAM in terms of spectral efficiency.

FQAM Modulation

Feher's Quadrature Amplitude Modulation is a mix of Frequency Shift Key (FSK) and QAM. By cross-coupling the I and Q channels, FQAM improves performance at the cell edge.

Adaptive Coding and Modulation

ACM is used today in many point-to-point radio systems, and in 2G-4G systems there is a control loop that governs changes in modulation level based on the link quality. In the context of 5G, ACM implies that coding and multiple access schemes would be variable in addition to the modulation level.

3 SPECTRUM

Every year, the picture gets a little bit more clear with regard to frequency bands for 5G broadband operation. Some consensus has become clear in bands below 6 GHz in the near term, and millimeter-wave bands have been identified by operators and by the ITU through the WRC-15 meeting.

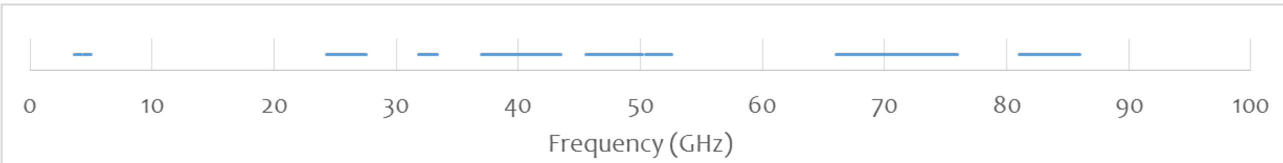

Figure 11. Spectrum blocks considered at WRC-15 for 5G

Source: WRC-15

Near Term pre-5G Bands

For pre-standard 5G deployment, mobile operators have identified specific bands in a few key countries:

- United States: Old LMDS spectrum at 28 GHz and 39 GHz has been acquired by mobile operators, for fixed broadband application of pre-5G links. The bands between 3.3-3.5 GHz and 3.7-4.2 GHz are possibilities for 5G allocation, but are also heavily sought after by Google and other unlicensed users.
- Japan: The Japanese Ministry of Post and Telecommunications has not made an official announcement to our knowledge, but Japanese operators clearly expect that the 4.5-4.8 GHz band will be allocated for 5G in Japan in advance of the 2020 Olympics.
- Korea: The 27-29.5 GHz band will be licensed for 5G use during the February 2018 Olympic games. No other services are licensed in this band so we expect the Olympic grant to be extended indefinitely. In addition, the government has announced plans to allocate some 1.3 GHz spectrum to KT, SKT, and LGU+ to cover the low-band 5G requirements. The bandwidth available for the low spectrum is not known at this time.
- China: The band between 3.4-3.6 GHz has been assigned for 5G trials, with additional spectrum at 3.3-3.4 GHz, 4.4-4.5 GHz, and 4.8-4.9 GHz possible for 5G as well. Allocation of these bands depends on mobile vs. fixed-use trials that are underway through October 2017. The 26 GHz band is under consideration by the Chinese government for 5G currently. Reportedly, the Chinese government has signaled plans to use a market-based approach (auctions) to license 5G spectrum. One industry insider reported that he believes China Mobile will receive 100 MHz, while China Unicom and China Telecom are likely to get 50 MHz each.
- Note that ZTE is proposing a unique allocation of 5G spectrum in China, with 3.5 GHz used as the downlink band and 1.8 GHz used for uplink. The configuration of LTE would be based on TDD, despite the separate uplink and downlink bands. Support for this proposal is spotty, but we've put this concept on our radar screen as a possible configuration.

Long Term Outcomes

From 2017 through 2020, mobile operators will "make do" with the bands that we have already been able to identify. Non-Standalone (NSA) networks will dominate during this time, due to spectrum issues, but also because the stand-alone network standards will not be ready until late 2019.

In the longer term, dual-band 5G networks will become normal and natural, because all of the bands identified below 6 GHz provide too little bandwidth. There's not enough spectrum below 6 GHz for each of three or four operators to receive an 800 MHz block. Therefore, low-band spectrum (with good coverage) will be paired with high-band spectrum (with wide bandwidth for capacity). World governments do not understand this basic requirement yet, so we expect a long period of waiting for either low-band spectrum or high-band spectrum to be licensed.

In the 2020-2025 timeframe, it's some LTE networks might begin to be re-farmed to 5G. In some cases this will be available in the BBU through a software upgrade, and if radio capacity is not a factor, the existing RRH might be used also—without taking advantage of Massive MIMO. The capacity benefit for this type of upgrade would be too small to justify the change, but if there's an advantage to creating a Stand-Alone 5G network with both low-band and high-band spectrum (for reasons related to core network performance, MEC, or raw capacity) then we will see the existing LTE bands transition to 5G.

However, a more likely outcome in the 2020-2025 timeframe will be for LTE to keep running, with additional deployment of 5G at 3.3 to 4.9 GHz. Even if only 100 MHz is available in this low band regime, the higher capacity of Massive MIMO and mm-wave aggregation should satisfy growing data demand.

The Role of the WRC

The WRC-15 meeting was intended to identify specific bands and to make firm decisions to harmonize allocation of key bands below 6 GHz to mobile telecom services. There was some success along these lines, although the ITU did not achieve its goal of allocating more than 1340 MHz of spectrum to IMT services by 2020. Here are some notes on specific bands:

- 470-694 MHz spectrum was not uniformly adopted with some regions (specifically EMEA region countries) sticking with terrestrial broadcasting.
- 694-790 MHz spectrum was more successful, with movement toward harmonization in EMEA and APAC countries to match the Americas.
- The 1427-1518 MHz band (which is already used for telecom in Japan) was moved one step closer to IMT services in the Americas and Asia, but not in Europe.
- 3300-3400 MHz spectrum was identified for mobile services for the first time with 33 countries in Africa, 6 in Latin America, and 6 in APAC joining together.
- 3400-3600 MHz spectrum has reached nearly global designation for mobile telecom.
- 3600-3800 MHz is not as globally recognized, with some countries opting for a smaller 3600-3700 MHz band.
- The 3800-4200 MHz band did not get designated for mobile telecom in this meeting.
- Similarly, 4400-4500 MHz did not get designated for mobile services.

- The 4800-4990 MHz band was designated for mobile services.

Overall, this story is not complete because each country can simply choose to use any band for mobile services as it sees fit.

Notably, the WRC discussion designated all of the bands below 6 GHz as "4G" bands, and most of them have already been identified in a few countries for 4G services. We expect that the designated LTE bands (up to 3700 MHz) will use LTE, wherever channel bandwidths are 20 MHz. Wider channel availability (such as the 3.5 GHz band in China) will migrate to 5G NR. Newer "5G" services with wider channel bandwidths are likely to be introduced between 3100 MHz and 4990 MHz In particular. For 5G below 6 GHz, we will be tracking the bands at 3400-3600 MHz, 3800-4200 MHz, 4400-4500 MHz, and 4800-4990 MHz as the most likely blocks.

The millimeter-wave bands proposed at WRC-15 include:

- 24.25 – 27.5 GHz
- 31.8 – 33.4 GHz
- 37.0 – 43.5 GHz
- 45.5 – 50.2 GHz
- 50.4 – 52.6 GHz
- 66.0 – 76.0 GHz (note this is not aligned with the USA's study of 64-71 GHz)
- 81.0 – 86.0 GHz

Notably, the 28 GHz band that has emerged as the primary pre-5G frequency band in the USA and Korea is not on the WRC list, because the ITU has the 28 GHz band listed nominally as a band for fixed services. Each country will need to decide on its own to designate 28GHz as a mobile band.

4 REGULATORY REQUIREMENTS

Many kinds of regulatory requirements can impact the development of 5G, and each regulatory entity creates rules for different reasons. Here's a basic overview of the types of requirements that 5G networks will contend with:

- Interference regulations on satellite/terrestrial/mobile use of spectrum;
- Interference rules to protect competing operators from each other;
- Safety rules to prevent electrical fields and RF power levels that could cause health concerns;
- Customs regulations to prevent the export of sensitive technology (this is most applicable for US semiconductor suppliers, with components that are useful in radar systems)

Interference over wide bands: Will 5G interfere with satellites?

The process of regulating the use of radio equipment usually begins with the government's overall philosophy about how to segregate different kinds of radio systems. Most advanced economies have set aside key bands for terrestrial systems, and another set of bands for satellite systems. The reason is simple: satellite transmitters are relatively weak and the receivers in low-cost satellite receivers are not perfect.

As an example, consider GPS receivers at 1.575 GHz. Most mobile and other terrestrial communications systems have been cleared out of the 1.5 GHz band because the GPS signals coming from the satellite are very weak, and the low-cost GPS receivers in billions of devices depend on low interference levels in the spectrum surrounding the GPS band. It's not enough to simply transmit at 1.579 GHz, because the receiver filters are not sharp enough to reject a signal that is near the transmitted signal. For this reason, the ITU and each government identify entire sections of the spectrum that are dedicated to similar services.

For mobile 5G, this concern can be overcome in many cases. For example, the 28 GHz band is currently designated as a band for fixed terrestrial services, but multiple governments have indicated their willingness to waive this requirement to allow mobile usage.

On the other hand, satellite bands are a concern for mobile 5G. L-band (1.5 GHz), C-band (4 GHz), and Ka-band (18-26 GHz) satellite systems will all require fairly clean surrounding spectrum, so government authorities must proceed with caution and a lot of testing in considering adjacent mobile services.

Interference over narrow bands: Will 5G operators interfere with each other?

As we predicted last year, government agencies are now starting to allocate 5G spectrum for competing operators in adjacent bands. The Japanese government plans to license the 4.5 to 4.8 GHz band in three equal blocks of 100 MHz each, without guard bands in between.

As a result, the mobile operator needs to consider whether a guard band is necessary for effective 5G performance. In this scenario, there are some significant differences with the famous "near-far" problem that confronted 2G through 4G systems:

1. Beamforming in the 5G transmitters results in a reduction in overall interference. From a statistical point of view, the directional beams eliminate interference in both infrastructure and client devices. This factor is tempting, because it suggests that interference levels are lower.
2. In cases where a competing transmitter lies in the same direction as a faraway transmitter, however, the relative interference levels in a 5G system can be higher than 2G through 4G systems. In Figure 12 below, the "aggressor" signal can block the desired signal in the "victim" receiver.

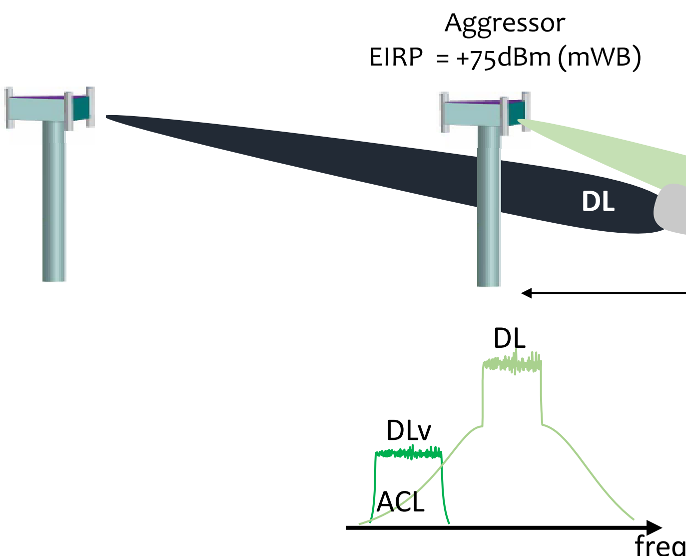

Figure 12. Anticipated mobile 5G interference scenario—Base Station Aggressor

Source: Qualcomm/3GPP

3. TDD-based systems can also experience interference in a similar scenario, where the "aggressor" UE transmits in very close proximity to the "victim" receiver. Because mobile 5G is set up as a TDD technology, uplink signals on the competing network can be transmitted during a downlink frame for the victim. Additional field testing is necessary to assess the potential impact of this scenario.

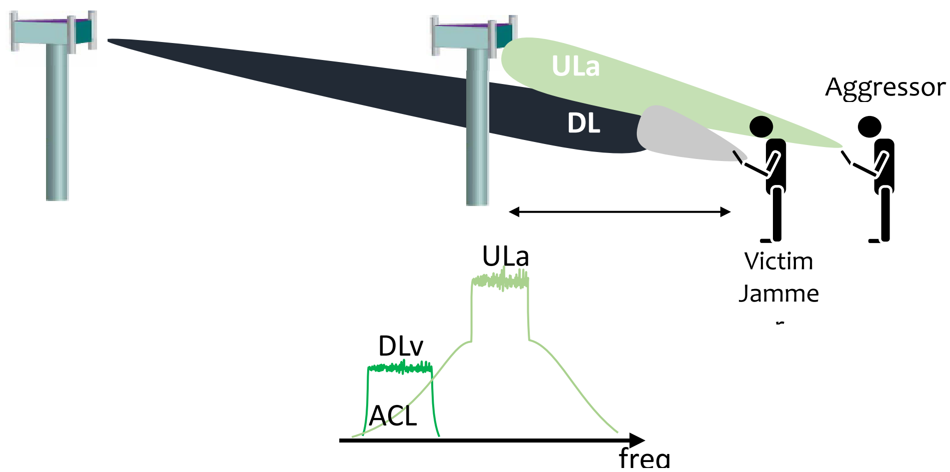

Figure 13. Anticipated mobile 5G interference scenario—UE aggressor

Source: Qualcomm/3GPP, modified by Mobile Experts

Safety Limits: Will 5G cause cancer?

As we change from 4G to 5G, there are two meaningful changes from a safety/health point of view.

Firstly, the higher frequency of the radio wave makes the electromagnetic energy level higher for each photon. In other words, when the radio wave is treated as a form of light, each quantum of energy is higher in the mm-wave bands.

Secondly, the beamforming systems used in 5G will result in higher effective radiated power as experienced by the user. A transmitter with an omnidirectional antenna spreads the energy uniformly, but the 5G transmitters will concentrate their energy directly at the users.

The major question here is whether the change to 5G is significant enough to impose any new rules for health and safety reasons. So far, the government agencies are relying on pre-existing rules for EIRP and field strength to guide the activity.

In the USA, the FCC uses Specific Absorption Rate, along with tight spurious emissions limits, to control transmitters below 6 GHz. Health concerns are normally handled through certification of each device in a SAR test. Above 6 GHz, the FCC uses a general power spectral density limit of 90 pW/cm2, at a 3 meter distance, to determine safety for humans. For handheld products, the tests are often more complex, with test distances of 5 cm and 20 cm and modeling to compare to the PSD limits. Any 5G implementation with a steerable beam in the handset could violate the power spectral density rules of the FCC, so we expect new rules to be considered during the next four years. The outcome of these rules is totally uncertain at this time.

Customs Regulations:

In the past, mobile technology has not exceeded the limits set by the US government for control of military technology. The American government has impacted the market in some cases, most notably when they imposed a ban on US semiconductor products exported to ZTE, as a punishment for ZTE's violation of Iranian economic sanctions agreed in the UN. 5G radio systems bring up a new consideration, with beamforming systems that closely mimic the performance of a high-speed radar system.

In particular, there are multiple component types that could be subject to control:

- MMICs or amplifier devices above specified power levels (lower power levels at higher frequencies)
- Phase shifters and related integrated circuits;
- High-speed ADCs and DACs, with specified limits on sampling rates and resolution

Specifically, integration of phase shifter devices into highly integrated modules may not be permissible for American companies that supply these components. The real impact on 5G hardware is likely to be a restriction on the level of integration, and in the end this should not be a limitation on the final capability.

Spurious Emissions Mask/OOBE

While not technically a "regulatory" issue, the spurious emissions mask requirements for mobile transmitters can sometimes violate the noise floor limits set by regulatory agencies to govern wideband performance. In other words, the out-of-band emissions requirements could be dictated by a government rule on spurious emissions. It's more likely that 3GPP limits will be more stringent than government limits in this regard, and in fact over the past 10 years almost all world governments have deferred to 3GPP in setting spurious emissions requirements inside mobile bands.

5 System Level Implementation

At a high level, 5G service will be an extension of LTE, with multiple simultaneous goals:

1. Faster, cheaper broadband data;
2. Ultra-reliable, low latency IoT connections;
3. Massive IoT connections.

These three objectives are somewhat incompatible, causing the overall 5G concept to be stretched in multiple directions at the same time. To some extent, the IoT applications are intended for low-band (below 2 GHz) spectrum, while the broadband applications are intended for high-band (above 2 GHz) spectrum. This inherent difference will solve the biggest challenges in the radio, so the remaining challenges are addressed in the communications format and the overall network architecture.

The incompatibility of broadband and IoT applications is somewhat handled by the "network slicing" concept… which is a convenient way to say that different network elements will come into play only for the applications where they're needed. Overall, the cost of network slicing is that processing horsepower must be distributed through the network so that each location has the ability to contribute to the overall capacity as needed. This gets expensive.

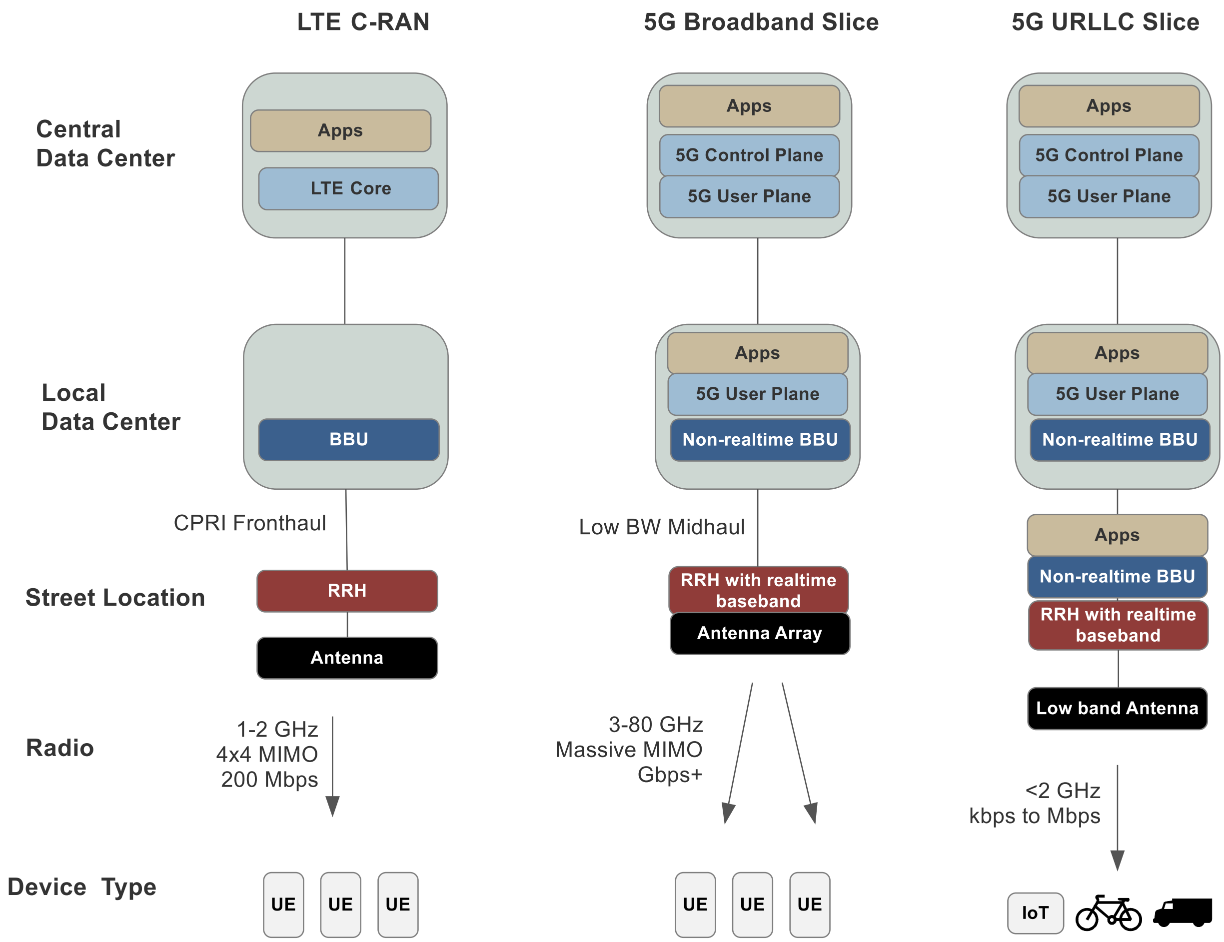

Figure 14.   Overall 5G architecture for Broadband and IoT slices

Source: Mobile Experts

Essential elements of the overall 5G network include:

- A virtualized packet core.   Separating the control plane and the user plane through the EPC is an important part of setting up network slicing.   At the same time, the core network must be migrated to standard servers to bring the cost down for dedicated hardware.
- Local data centers will add more functionality, with some applications and user plane core network functions moving from the central data center to provide lower latency.
- The baseband processing will be re-partitioned so that the high-bandwidth requirements of CPRI will not extend to the 5G Broadband case. Realtime functions in the PHY and the lower MAC will be physically performed in the remote radio head, while non-realtime baseband processing (upper Layer 2 and Layer 3) will remain in the local data center for most broadband applications.
- The Remote Radio Head will take on PHY/MAC, and will be integrated with the antenna array for frequency bands above about 3 GHz so that Massive MIMO can be achieved without electrical losses between the RRH and the antennas.
- The IoT slices of the 5G network may use very different partitioning, with low-latency applications requiring applications, core network and baseband functions to be moved closer to the user.
- Note that the IoT applications are most likely to run at frequencies below 2.7 GHz, so the Integration Antenna Radio concept is not likely to apply.   On the radio hardware, "network slicing" does not help because the radio hardware will look very different for the broadband and IoT slices.   In fact, for some cases existing GSM or LTE antennas and radios may be utilized for 5G IoT.

Mobile Edge computing is also a major thrust of the 5G network.   MEC will open up possibilities for monetization of the network, and will improve the efficiency of the overall network by collecting data for analysis near the edge…thus avoiding the need to send many gigabytes or terabytes of data through the entire network.   MEC servers can be placed at the edge with the radios, or at any data center location.

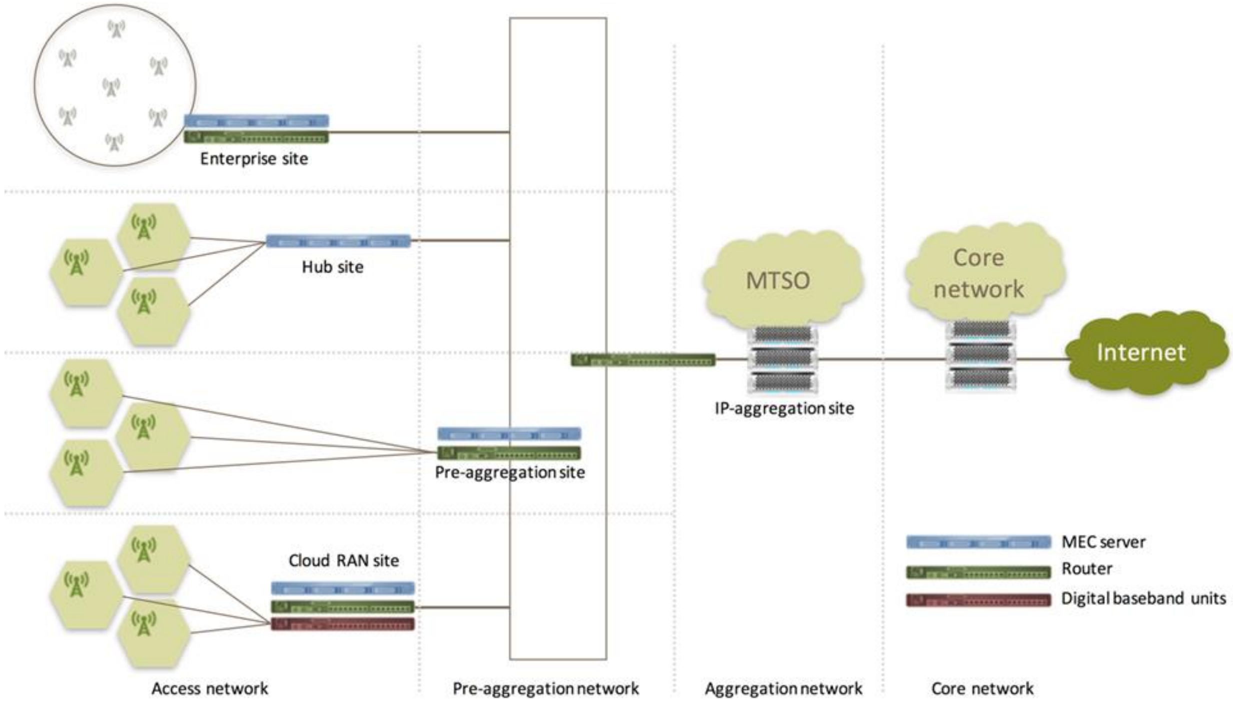

Figure 15. Overall 5G system architecture with Mobile Edge Computing

Source: XONA Partners/Mobile Experts

6 Radio Implementation--Infrastructure

In last year's report, we presented some issues related to radio implementation, with regard to beamforming and EVM errors, linearity of amplifiers, and physical construction of a mm-wave radio. Over the past year, the solutions to these questions have been resolved, and the practical implementation of 5G Broadband networks is becoming more clear. Not all questions are answered yet, but we believe that the major hurdles have been lowered enough to make success likely.

Digital and Hybrid Beamforming

The ultimate desire for most radio engineers is to achieve the ultimate in digital beamforming, with the DSP processing cores setting phase and amplitude for each element digitally. The result in this case is the simple, clean block diagram shown on the left side of the below diagram. For bands below 6 GHz, where the bandwidth remains below 100 MHz or so, the digital beamforming approach is likely to be used widely. The main drawback of the pure-digital beamforming technique is related to power consumption, as the correction of wideband steering for a large array can be very computation-instensive.

Above 24 GHz when side bands and wide steering angles are required, the power consumption of a digital beamformer can be prohibitive, so the major OEMs have considered analog beamforming. The analog approach has been used in radar systems for more than 60 years, and works great for narrowband signals. Analog beamforming allows for narrow beams using a lot of elements, but it lacks the flexibility of a digital beamformer.

In particular, one issue with using a pure-analog approach is that analog beamforming only works well for narrowband signals. Wideband signals that are steered with simple analog phase shifters result in significant EVM errors, because the phase shift is only accurate for the center frequency, not the band edges.

To get the best combination of high gain (narrow beams) and the flexibility of digital processing, variations on the hybrid approach will be used by all major OEMs. In essence, the hybrid approach allows grouping of antenna elements to keep the number of RF paths to a minimum, while still allowing for a large number of elements and the corresponding narrow high-gain beam.

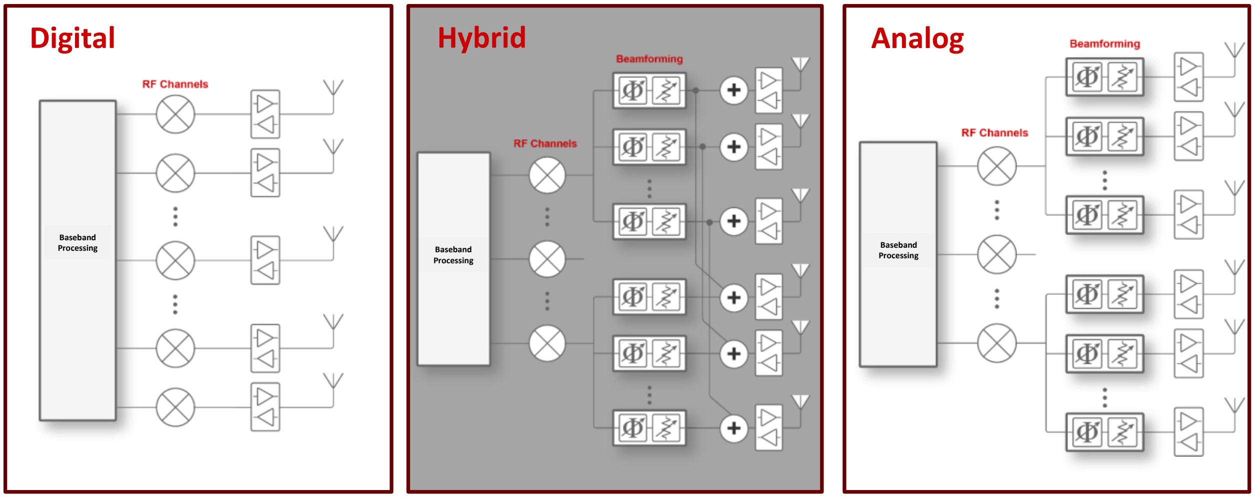

Figure 16. Block Diagrams for Analog, Digital, and Hybrid Beamforming

Source: Peregrine Semiconductor

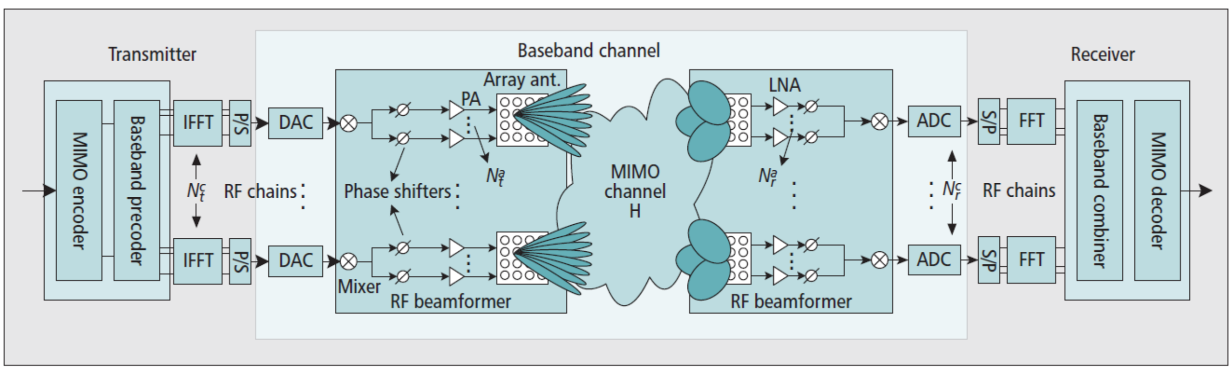

Figure 17. Hybrid Beamforming—end to end diagram

Source: Samsung

GaAs, GaN, SiGe, or CMOS? 5G mm-wave Power Amplifiers

The choice of semiconductor process for 5G amplifiers is important, because it's a tricky balance of output power, linearity, and efficiency. At 3-6 GHz, the power amplifier process technology is likely to be GaN, as an extension of the devices used today at 2.5 GHz and 3.5 GHz. Above 20 GHz, the choice is more complex.

For mm-wave amplifiers, the brute force method (used in many trials so far) results in a huge heat load in the range of 600W or higher. This approach is not supportable in a real-world product because the mobile operators will not accept the giant air conditioner on top of a streetlight. It's okay for a prototype system, and we now see some indications of the improved prototypes that can achieve similar performance with a lower heat profile.

In considering this question, a few key assumptions must be listed:

- Multiple deployment scenarios will apply, including indoor, dense urban, and urban cases. Each scenario will involve different transmitter power levels.
- The Peak-to-Average Ratio of the waveform is expected to be 11-12 dB.
- ACLR requirements will be set to about -30 dBc. This estimate is based on Ericsson's input to the 3GPP RAN4 committee, indicating that ACLR requirements tighter than -35 dBc yield little benefit (and are probably not achievable in practical systems).

Deployment Scenarios

In the 3GPP discussions, multiple deployment scenarios are used to illustrate important cases. We've chosen three key scenarios, based on the potential market size of different deployment options.

1. Urban Deployment: The biggest initial market is likely to be the equivalent of a "macro base station" deployment in 5G, involving the widest possible coverage from existing LTE sites and some additional sites. Most OEMs are modeling this deployment with inter-site distance of 200m or 300m. For simplicity, we assume a maximum link distance of 200m.

   In this case, the transmitted power level from the 5G site will be as high as possible in order to maximize link distance. Some players are considering grouping antenna elements, for example driving a column of antenna elements with a big GaN amplifier to avoid difficult integration challenges. This creates its own problems with feed lines, loss, and lower gain. This approach will only work if ACLR specs require it… and right now the political winds are favoring ACLR specs that SOI or SiGe can meet.

2. Dense Urban Deployment: In many cases the 200m link distance is not realistic because the density of buildings and users is so high that smaller sectors are desirable. A stadium example or a Multi-Dwelling Unit (MDU) example could fit this deployment model.

   For dense urban base stations, the RF power from the array may be reduced to avoid interference from reflections into other nearby sectors. Bulk silicon, SOI, or SiGe could be viable candidates in this scenario.

3. Indoor Small Cells: The indoor small cell will be designed around SOI amplifiers, with OEMs on track to accept whatever power level they can get. In fact, the RF composite power level will depend more on the number of T/R elements in the array, not on the semiconductor process. Bulk CMOS RF front ends are likely to win here.

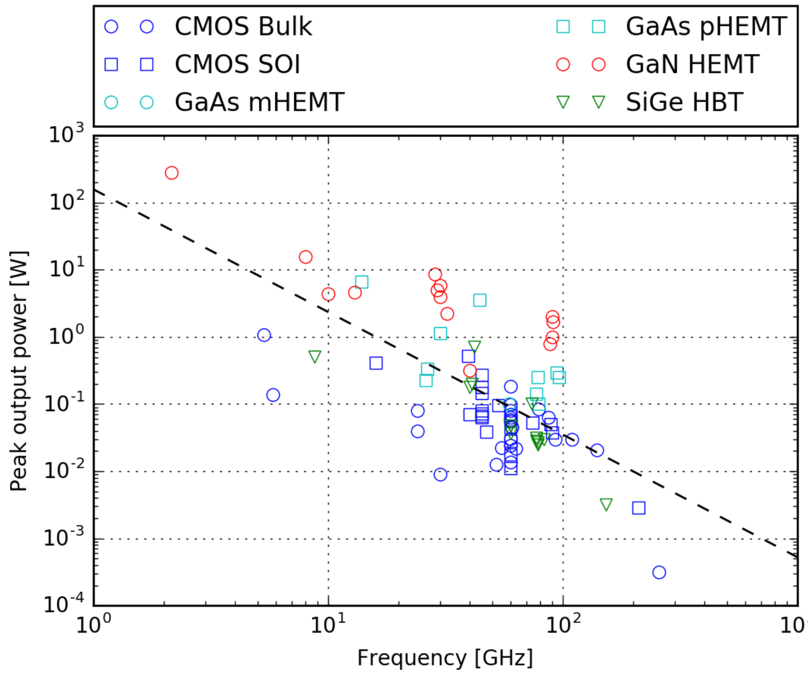

Figure 18. Comparison of CMOS, SiGe, GaAs, and GaN for mm-wave peak power capability

Source: 3GPP RAN4

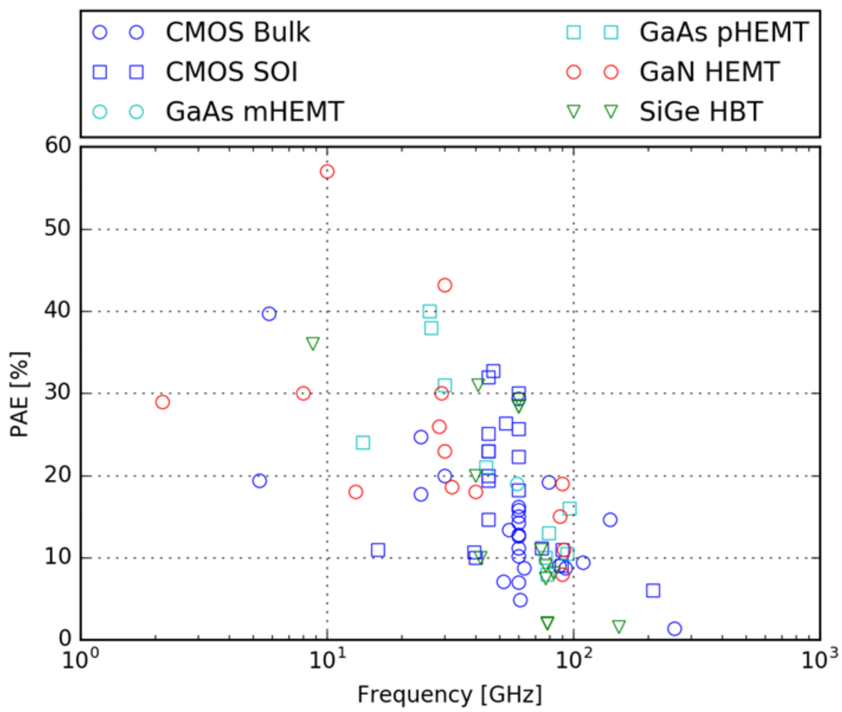

Figure 19. Comparison of CMOS, SiGe, GaAs, and GaN for mm-wave PA efficiency

Source: 3GPP RAN4

The two figures shown above tell the story of GaN and SOI. GaN provides up to 10W of peak power per device at 28 GHz, with 40% power-added effiency. SOI can achieve about 30-33% PAE, at peak output power well below 1 W. Field trial systems with individual SOI and SiGe amplifiers at +13 to +15 dBm each have been able to reach between 200 meters and 1 km range, due to antenna gain that puts the Effective Incident Radiated Power (EIRP) in the range of +47 dBm. We now expect this to be the primary deployment for 28 GHz infrastructure.

The mobile operators and major OEMs would prefer to reach EIRP levels of +55 to +65 dBm, for higher signal to noise ratio at long distance. This may be possible, with some tradeoffs in beamforming complexity to reduce the number of power amplifiers involved. One possible configuration could be to eliminate vertical beamsteering, using higher power GaN or other power amplifiers for an entire column of antenna elements, retaining steering in the horizontal direction.

Because the typical regulatory EIRP limit is +75 dBm, an architecture that achieves higher power will get some attention by OEMs and operators. Currently these systems are not mature enough to be demonstrated at trade shows, but we expect to see them about 2-3 years from now.

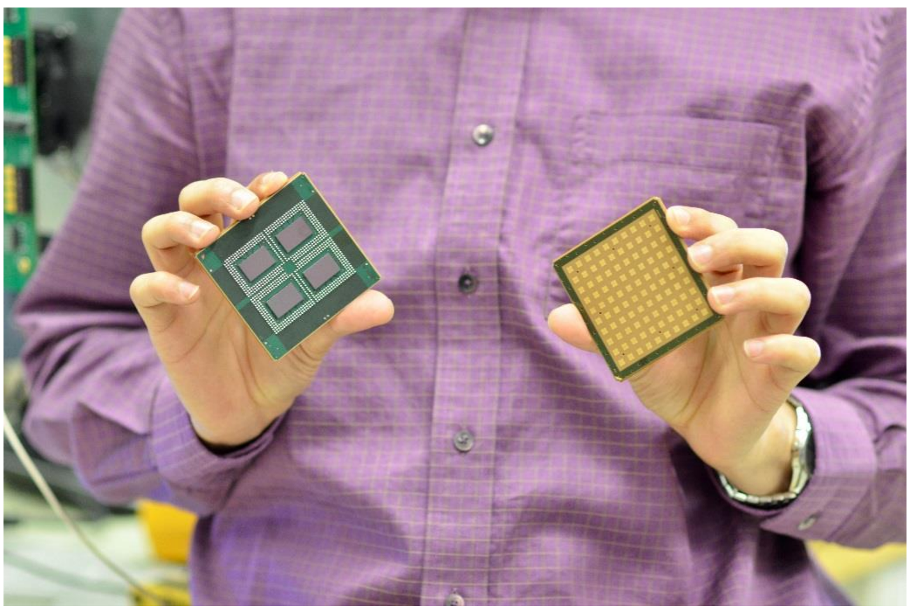

Figure 20. The IBM-Ericsson antenna array and RF front end at 28 GHz

Source: IBM

Ericsson and IBM have recently announced the performance of a highly integrated front end using 130nm SiGe. Noise figure performance and efficiency look ok, but the linearity of the solution is not clear from the published results so far. Overall, from multiple inputs we believe that the linearity of SiGe will have an advantage over bulk silicon and SOI, but we cannot determine at this time whether it's enough advantage to outweigh the integration challenges of SiGe.

Peak-to-Average Power Ratio (PAPR or PAR)

Because the cyclic prefix, channel spacing, filtering, and other aspects of the waveform are still undecided, the PAR of the waveform is not known. So far, the PAR looks likely to be a bit higher than LTE. Early results indicate that without taking extra care, the PAR for FBMC, UFMC, and GFDM would come out to about 17 dB.

Of course, the major OEMs have been working with waveforms to reduce PAR for many years. A typical LTE system that's actually deployed does not really drive an envelope at 11-12 dB PAR. By cleverly choosing PN sequences and resource blocks, the OEMs have proprietary tricks to reduce LTE PAR to about 8-10 dB. Based on our interviews so far, we can expect them to reach PAR of about 12-13 dB in the case of various 5G alternatives.

Waveform	LTE	FBMC	UFMC	GFDM
Unloaded PAR	12.15 dB	8.14 dB	10.44 dB	13.24 dB
Loaded PAR	11.11 dB	17.56 dB	17.27 dB	17.76 dB
Crest Factor Reduced PAR	9.5 dB	13 dB	12.5 dB	13 dB

Figure 21. PAR for LTE, FBMC, UFMC, and GFDM, including impact of CFR

Source: Rohde & Schwartz, Mobile Experts

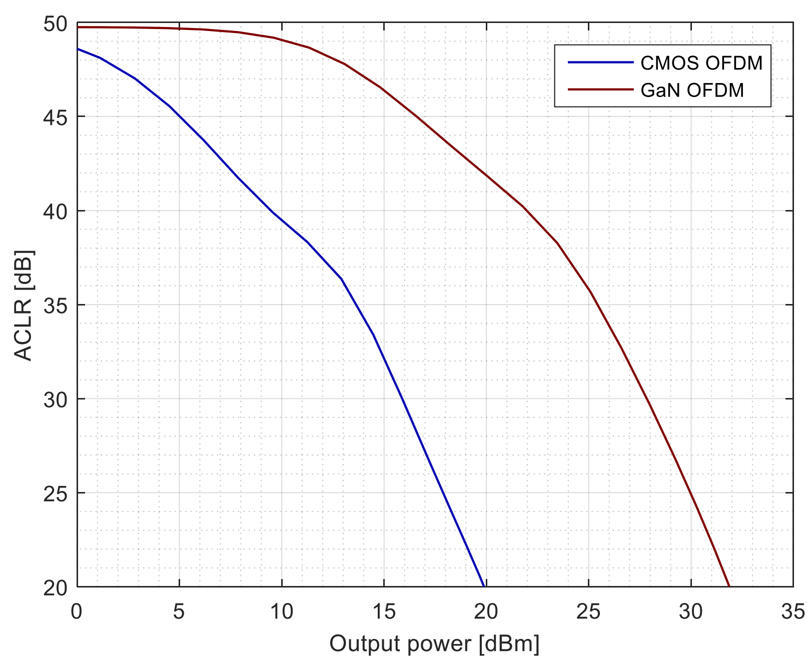

Figure 22. Comparison of GaN and SOI amplifiers for ACLR performance

Source: 3GPP RAN4

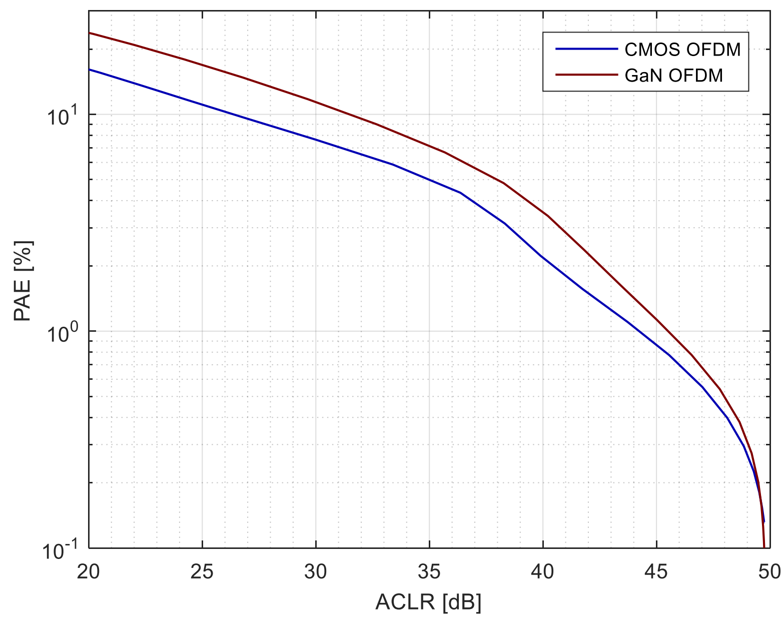

Figure 23. Comparison of GaN and SOI for PA Efficiency

Source: 3GPP RAN4

What about linearization?

For the past 15 years, all major OEMs have used digital predistortion routinely as a way to squeeze higher performance out of the amplifier. Linearization of the amplifier allows the system engineer to reduce the size of the PA, drive it harder, and achieve lower cost and higher efficiency.

Several OEMs have mentioned recently that the wide frequency blocks associated with mm-wave 5G bands are too wide for digital predistortion. This may be true, but we suspect that over time a solution will be found. Today, it's too early to make a conclusion about the mm-wave bands at 800 MHz and wider.

Narrower bands such as the 100-200 MHz spectrum blocks in the US market are more likely to use a form of linearization. The typical approach is to sample the output of the radio, to adjust the digital predistortion and maintain about 20-30 dB of error correction. It's not clear today how the sample path will be collected and fed back to multiple transceivers in an array. We expect this to happen, but today we don't have the implementation details.

Finally, we expect the majority of 5G infrastructure deployed in the 3-6 GHz bands to use GaN amplifiers, which inherently are not highly linear—therefore these systems will require a form of predistortion.

Specifying ACLR, ACIR, and ACS

The choice of semiconductor technology, in the end, may come down to a political decision in the 3GPP working groups. The working groups are considering the level of Adjacent Channel Interference Ratio (ACIR) that will be acceptable in 5G systems. This question is somewhat philosophical, in terms of how much margin is really required and whether the transmitter or receiver should be responsible for interference protection.

The ACIR formula is defined as

$$\mathrm{ACIR} = \frac{1}{\dfrac{1}{\mathrm{ACLR}} + \dfrac{1}{\mathrm{ACS}}}$$

Where ACIR is the Adjacent Channel Interference Ratio,

ACLR is the Adjacent Channel Leakage Ratio (transmitter cleanliness), and

ACS is the Adjacent Channel Selectivity (the sharpness of the receiver filter)

So, each OEM will have different ideas about the acceptable level of spurious emissions for their transmitters. Notably, companies with more field experience in mobile telecom systems have the lower proposals for ACIR specifications.

Company	Urban Macro	Dense Urban	Indoor
Nokia/ALU	20	16	9
Ericsson	22	20	18
NEC	15	20	15
Huawei	27	17	14
ZTE	25	15	18
Samsung	14	16	9
Qualcomm	20	20	20
Intel	20	20	20

Figure 24. ACIR proposals from various OEM suppliers

Source: 3GPP RAN4

In the end, our conclusion is that lighter ACLR specifications will be set for indoor 5G small cells, and a level of about -30 dBc will apply to high power outdoor deployment at mm-wave frequencies. This requirement is lighter than LTE requirements have been in the past, especially considering the use of waveforms that generate lower out-of-band emissions at the start. Note that below 6 GHz, we are more likely to see higher ACLR requirements of -40 to -45 dBc due to the presence of many other wireless services in nearby bands.

Input parameters	Value	Units
EIRP of serving BS, and also of aggressor BS's	75	dBm
BW	100.0	MHz
center frequency	28.0	GHz
distance from serving BS to UE	200.0	m
distance from aggressor BS to UE (ACS). Assume same direction.	15.0	m
NF of UE	10	dB
IIP2 of LNA	0	dBm
IIP3 of LNA	-30.0	dBm
Coex study ACLR value from BS to UE	23.0	dB
Desired EVM for coded QPSK	-1	dB
Element gain	5	dB
Array gain	6.0	dB
Integrated close-in phase noise	-30.0	dBc
Far-out Phase noise PSD (f > 50 MHz)	-130	dBc/Hz
Atmospheric absorption, and hand-blocking losses	50.0	dB
Path loss from signal source to LNA input (including antenna element gain)		
Path loss from serving BS to UE	152.4	dB
Path loss from aggressor to victim (ACS)	129.9	dB
Thermal noise and wanted signal @ LNA input		
input-referred thermal noise at UE = KTBF	-84.0	dBm
required power of wanted signal = input-referred noise - array gain + EVM of desired signal	-92.8	dBm
actual power of wanted signal. Compare with row above	-77.4	dBm
Blocker strengths relative to wanted signal		
Computed ACS ratio	22.5	dB
Power of ACS blocker	-54.9	dBm
SINR calculation @ LNA input		
power of desired signal and ACS blocker at antenna output	-54.9	dBm
input-referred IM2 terms	-109.8	dBm
input-referred IM3 terms	-104.6	dBm
thermal noise (copied from above)	-84.0	dBm
ACLR from BS to Rx path	-100.4	dBm
Reciprocal mixing of ACS blocker	-104.9	dBm
Close-in phase noise	-107.4	dBm
Desired EVM of signal (copied from input parameters)	-1	dB
SNR at UE input = desired signal / (inter-mod terms + thermal noise + "ACLR" + reciprocal mixing terms + close-in phase noise)	6.4	dB
Margin	7.4	dB
ACIR at the UE input = 1/((1/ACS) + (1/ACLR))	19.7	dB

Figure 25. Detailed link budget analysis to justify roughly 20 dB ACIR

Source: 3GPP RAN4

There is one more issue with regard to ACLR, involving the method for testing. In the past, every RRH had an RF connector, so testing was easily achieved using bench test instruments. With integrated antenna radio modules at 28+ GHz, the output of the transmitter cannot be easily tested in a conducted test. Therefore the industry is likely to migrate to a radiated emissions test.

In this case, the beamforming array can help to reduce out-of-band interference, because the array will not steer the out-of-band emissions in the same way as the in-band signals. In other words, the 5G antenna will also be a filter.

The following two diagrams illustrate the difference in adjacent-channel interference when a) the beamformer directs interference exactly the same as desired signals, and b) the beamformer spreads interference evenly through space. The actual case will be somewhere in between, reducing interference from out-of-band emissions by spreading the interference and not sending all of it to the "victim" receiver.

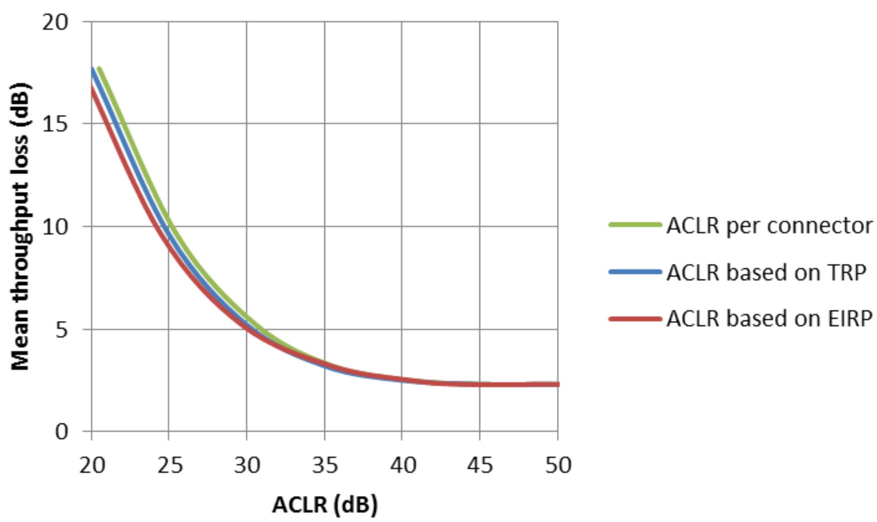

Figure 26. Coexistence performance when unwanted emissions are 100% correlated to desired signals

Source: 3GPP RAN4

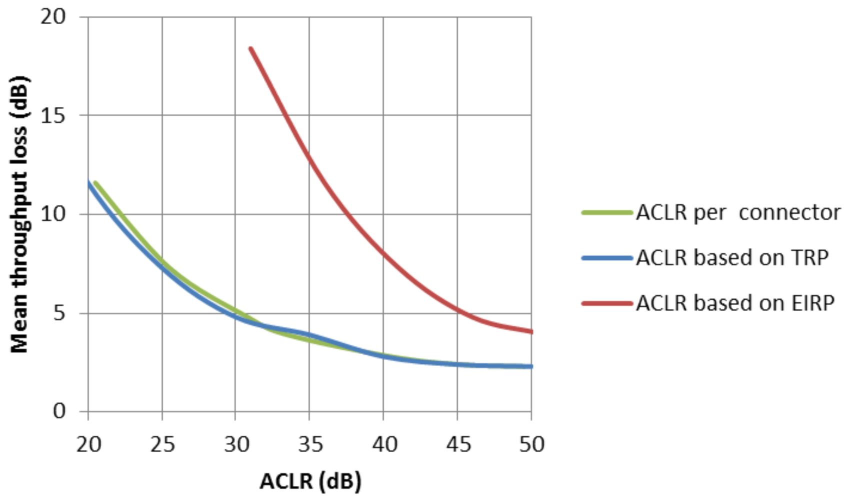

Figure 27. Coexistence performance when unwanted emissions are 0% correlated to desired signals

Source: 3GPP RAN4

Filters

Multiple OEMs have commented recently that RF filters may not be placed at the typical location in millimeter-wave T/R modules. This assumption is not yet proven, but it's possible based on a few factors:

- Beamforming gain will not be perfectly correlated for out-of-band signals, so the antenna array will provide some filtering in the frequency domain.
- The physical antenna element and the transmission line used to connect the PA/LNA components can be designed with filtering properties. Some innovative packaging concepts are in prototype systems now, with coplanar waveguide and other concepts to reduce loss for a narrow band.
- Emissions in the mm-wave bands are light. Satellite signals and radar systems are not likely to result in strong input to either base stations or client devices.

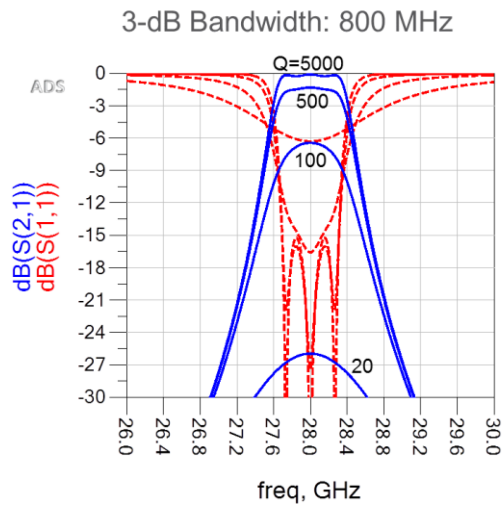

Figure 28. Insertion loss comparison for simple 3-pole filters at 28 GHz

Source: Ericsson

One major challenge here is that the low Q of filter components at the 28+ GHz bands results in unacceptable losses. A narrow filter would be likely to result in 3-6 dB loss, due to the Q value of typical distributed elements at mm-wave frequencies. Ceramic filters have Q values in the range of 300, while MEMS and other more exotic structures can reach Q values in the 500 range. With an 800 MHz filter bandwidth, this loss would still be unacceptable. Waveguides can reach Q values in the thousands, but fabricating waveguides for each element could be expensive.

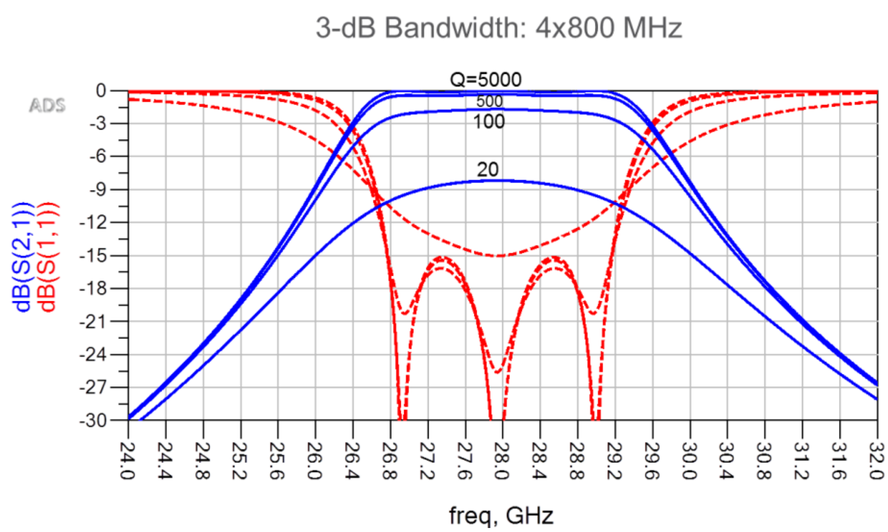

Figure 29. Insertion loss comparison for wider 3-pole filters at 28 GHz

Source: Ericsson

A more likely case will be for the OEMs to use wider filters. Losses below 3dB are possible for ceramic filters if the bandwidth is 4x wider than expected channels (about 3 GHz wide). Even this loss is likely to be unacceptable at the front end, so one likely case will be for this wider filter to be used behind the PA/LNA stages to account for LO leakage, image rejection, and intermodulation products.

In the end, a great deal more field testing will be required to understand the interference levels for adjacent band interferors, which will be the primary concern. It's too early to make a conclusion, but so far we recognize a possibility that filters will not be placed after the power amplifier/before the LNA as in 2G to 4G systems.

Note that, at 3.5 to 6 GHz, very small distributed filters will not be effective. We assume that a true filter component will be used in all of these systems. A band-pass filter in the case of a TDD system would be placed at the antenna, so that both PA and LNA would be subjected to the loss of the filter. A low-loss ceramic filter design is a likely outcome due to the size constraints and loss requirements.

Millimeter-wave Antenna and Transceiver Implementation

Putting it all together in a practical, low cost radio will be a challenge. Fixed broadband applications in NSA networks will be the first step: a 28 GHz (or 39 GHz) array will be implemented for each sector, with highly integrated transmit/receive modules as close to the antennas as possible.

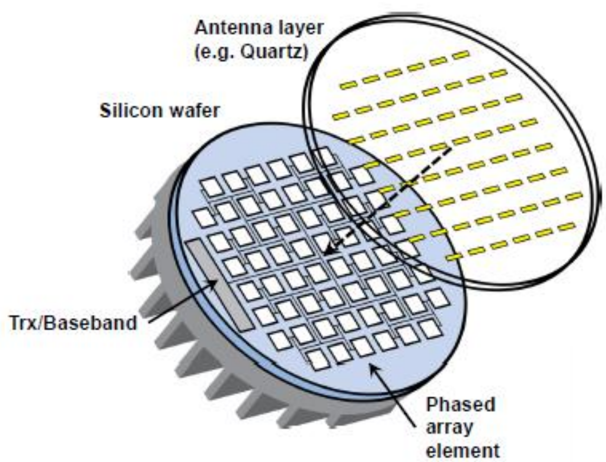

Figure 30. Construction of a wafer-scale assembly with an antenna layer and a transceiver layer

Source: UCSD

At a high level, the best way to describe this mm-wave integration is that Wafer Scale Packaging will be used to sandwich multiple component types together. Our simple example shows a silicon wafer with a quartz wafer on top as a carrier for the antenna elements. For a 5G front end, it's likely to be more complex, with a compound semiconductor layer for the RF front end components (the minimum set will be a switch, PA, and LNA). This is by no means guaranteed to be on a single layer, as the optimal process for each function could be different.

Early prototyping is underway now, so many possibilities can diverge from our example diagram below. The antenna carrier wafer could be simple glass, or could be an SOI or GaAs wafer to provide a platform for the switch or LNA. In the high power implementation shown below, GaN is the most likely candidate for the PA, so a great deal of attention will be paid to heat sinks to the central layer in the stack. Thermal vias, heat pipes, and other concepts that are not shown here are possibilities.

Will GaN provide enough performance benefit to justify the higher complexity of this kind of sandwich structure? Possibly in suburban deployment where link distance becomes super-critical due to high cost for each cell site, and higher EIRP is required for penetration of foliage and other obstacles. Today, the initial urban deployment cases seem to be using SOI and SiGe.

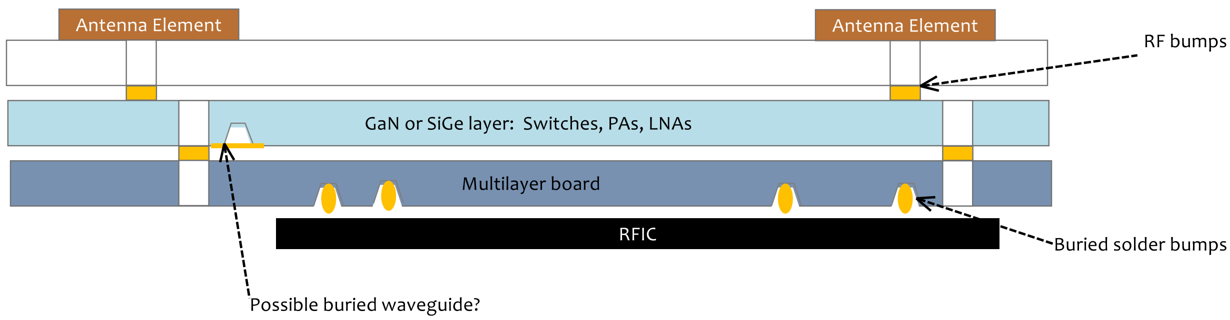

Figure 31. Possible construction of a high-power wafer scale assembly above 28 GHz

Source: Mobile Experts

In an indoor small cell implementation of 5G, it's now clear that the RF front end to collapse into a much simpler structure. There will be no need for the compound semiconductors on the front end, and the RF CMOS processes currently used for 802.11ad (WiGig at 60 GHz) will be adapted to the 5G case between 20 GHz and 70 GHz. The below illustration is one possible concept for low-cost implementation.

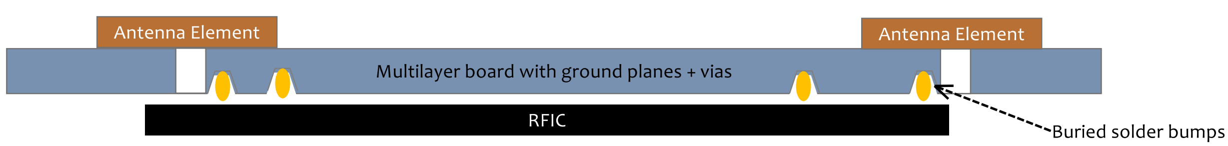

Figure 32. Simpler construction for a silicon 5G radio/antenna array

Source: Mobile Experts

2-6 GHz Semiconductor Implementation for mMIMO

The millimeter-wave radio needs completely new physical packaging, but at 3-5 GHz, many of the radio techniques used at 2.5 GHz can be adapted readily. So far, all of the top OEMs are using variations on GaN power transistors and GaAs LNAs that are familiar from traditional radio systems.

One direction of this development effort involves the use of "Front End Modules" which incorporate the power amplifier, switch, and LNA for each antenna element. The sheer number of antenna elements in a 2.5 GHz or 3.5 GHz antenna array means that tight packaging and low cost are high priorities… and several major OEMs are moving toward integration of these devices in a multi-chip module.

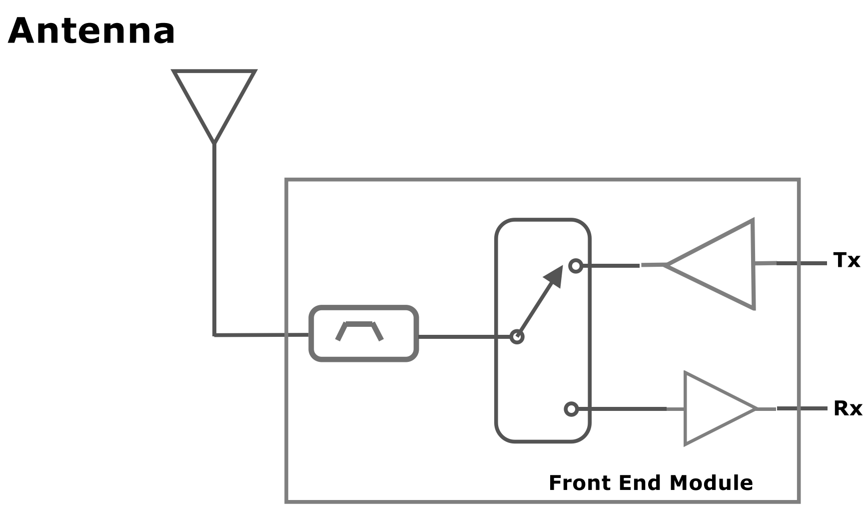

Figure 33. Block Diagram for a 3-6 GHz RF Front End Module

Source: Mobile Experts

5G Field Test Results

Several tests have been conducted using prototype hardware at 3.5 GHz, 4GHz, 15 GHz, 28 GHz, and a few other bands. As of February 2017, both fixed and mobile tests up to 100 km/hr have been performed to validate the performance of the link.

In general, the tests aim to prove the viability of 200 meter links or longer, in an urban environment with buildings blocking line of sight. Rain, foliage, and other tests have also been conducted by the top vendors with very little data shared publicly. Overall, the consensus is that high-gain antennas for the base station infrastructure and the CPE, low power RF transmitters can work. At only +47 dBm EIRP from a 28 GHz radio, trials have demonstrated as much as 1 km range.

Note that the long distance link performance depends on gain in the range of 25 dB at the RRH, and 10 dB or more at the CPE. In the case of a smartphone, high antenna gain is far less likely, and something will need to change.

Early Adoption of Massive MIMO in LTE

China Mobile and Softbank are currently deploying Massive MIMO as an upgrade to TD-LTE at 2.5 GHz. This is not simply a novelty or a special case: roughly 5000 cell sites will be upgraded by mid-2018, and we expect additional China Mobile sites to follow during late 2018 and 2019. Sprint may also adopt this approach, subject to availability of capital for upgrades.

The default configuration of Massive MIMO in TD-LTE is a 64T/64R transceiver set, with cross-polarized antenna elements resulting in 128 elements total. The early deployment is urban, so the antennas are arranged in an 8x8 pattern for both horizontal and vertical beamsteering. Future suburban to rural deployment will use a 4x8 or 4x16 pattern, for limited vertical steering and either cost improvement or tighter horizontal beamwidth.

In addition to TD-LTE, Massive MIMO has now been deployed in FDD LTE systems. Blue Danube has two trial sites working on commercial sites in the USA today, achieving spectral efficiency in the range of 10 bps/Hz. In addition, Vodafone has deployed a system in Germany with a significant boost to their capacity in a "town square" urban center.

Figure 34. Commercial field trial of Massive MIMO in FDD LTE

Source: Blue Danube Systems

Note: Mobile Experts includes LTE Massive MIMO systems in its Macro Base Station Transceiver forecast, but the LTE units are not counted in the 5G forecast.

7 RADIO IMPLEMENTATION—USER EQUIPMENT

The implementation of the base station radio is focused on big antenna arrays, high power, and moving a lot of heat. In the user equipment, the antenna array will be smaller, but cost challenges and practical antenna considerations make implementation difficult.

Fixed Broadband: CPE Implementation

The early implementation of 5G in the USA will involve customer premises equipment on fixed locations. Both Verizon and AT&T are implementing 28-39 GHz fixed broadband networks in which the CPE will established a fixed link with a nearby 5G site.

The early specifications called for indoor CPEs similar to a Wi-Fi router or a set-top box… essentially a box that can be placed somewhere inside the house. Unfortunately, the penetration of the mm-wave signal through a typical wall is so poor that this idea is unlikely to succeed. Instead, a variety of CPEs are envisioned that can be mounted in the window, on a wall, or on the subscriber's roof.

The CPE will include a steerable antenna array which will generally lock into a static position based on the placement of the unit and the base station. Line-of-sight operation is preferred, but NLOS placement may be used in some cases as well.

So far, we have heard about multiple variations on the CPE, so the final configuration is not clear. The array is likely to include 4-12 elements with limited vertical beamsteering (this could be mechanical) and finer horizontal beamsteering. We expect a mixture of rooftop units (far away from a 5G site), window-mounted units (medium distance) and some indoor units (close to window?).

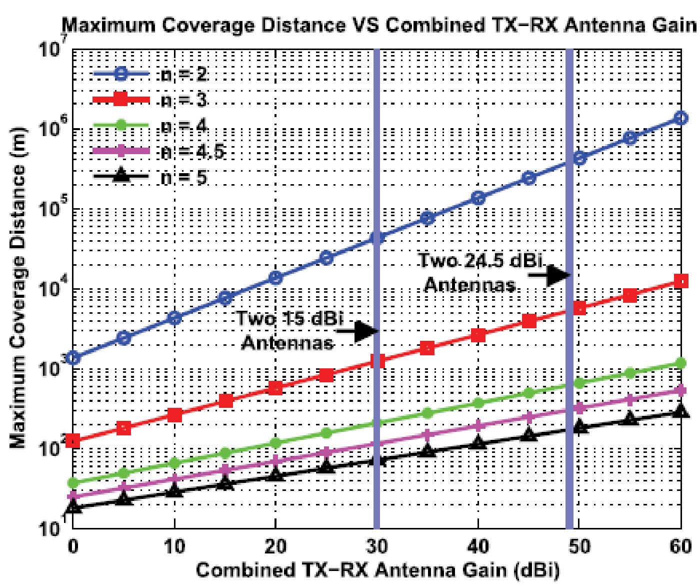

Figure 35. Modeling of RF link distance as a function of combined Tx/Rx antenna gain

Source: Professor Ted Rappaport, NYU

Mobile Broadband: 5G Handset Implementation

For true mobile performance in a tablet or handset form factor, new issues arise. The most problematic consideration is the attenuation of the human hand on a 28+ GHz signal. Measurements by Samsung and others indicate that a human hand (or any similar-sized object with heavy water content) will attenuate a 28 GHz signal by 30-40 dB. This is enough to kill the 5G link.

To compensate, the handset OEM is likely to use antenna diversity. In other words, they will use multiple sub-arrays. In one such example, the handset would include a 28 GHz array, with subarrays on each end of the phone, so that even large hands cannot cover all antenna elements easily.

In this configuration, eight antenna elements are placed at each end of the PCB in the horizontal plane, and eight more elements are placed in the vertical plane—for a total of four subarrays in the handset. The RF semiconductors would ideally be discrete devices, placed immediately behind each antenna elements with no transmission lines. We believe that 32 RF front end modules would be too expensive, so we've built our cost estimates around the use of 2 RF modules for a set of 4 antennas—in other words, a total of 8 RF modules in the handset.

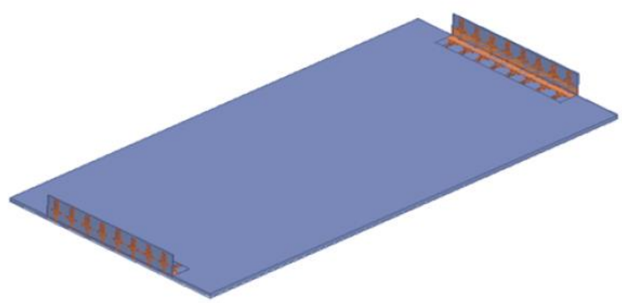

Figure 36. One possible implementation of four sub-arrays in a handset

Source: Shanghai University

A further challenge is the three-dimensional pattern requirement from the handset. People don't hold their handsets in an RF-friendly orientation all the time. This means that a mm-wave antenna array in the handset must include the ability to steer in three dimensions. We expect the steering and switching of multiple elements to become highly sophisticated in a smartphone application, because the hand will cover arbitrary elements while leaving other elements open. The algorithm will need to figure out how to optimize the antenna pattern with the antenna elements available.

The sub-array in a handset is unlikely to achieve high gain due to cost and space constraints, but academic papers released so far indicate that 6-10dBi is a reasonable estimate for handset array gain.

Antenna sub-arrays

Each antenna sub-array can provide a steerable pattern in two dimensions, but the handset is a three-dimensional challenge. That's why two arrays will be situated at each end of the handset, in order to achieve a pattern which is adaptive in all three dimensions.

This fairly straightforward exercise is complicated by the presence of the user's hand. At 1-2 GHz, the hand has an impact on the antenna pattern, reducing Total Radiated Power by 5-6 dB in some cases. However, at 5 GHz the impact could be more than 10 dB and at 28 GHz the impact could be a devastating 30 dB.

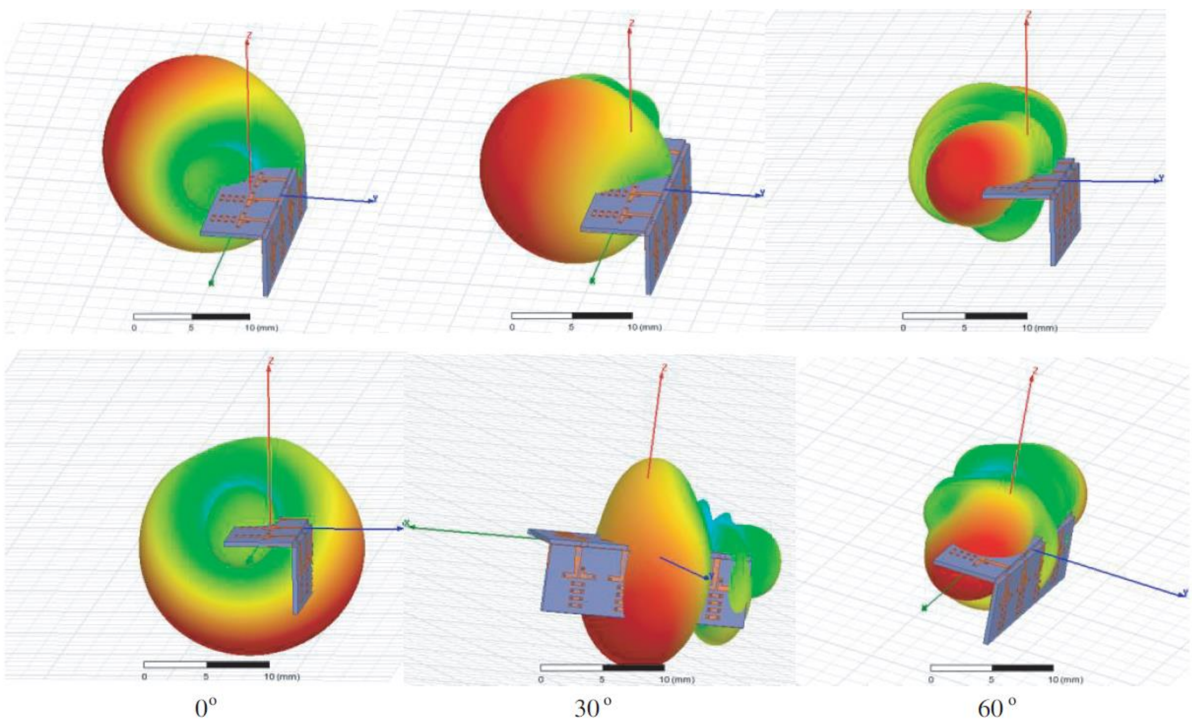

Figure 37. Various antenna patterns achieved with four 28 GHz antenna subarrays

Source: Shanghai University

To compensate for unpredictable hand placement by the user, the combination of antenna elements must be extremely flexible, allowing any combination of elements in the array to optimize the best possible beam pattern.

Many of the link budget assumptions used currently by network OEMs are assuming about 8-10 dBi gain from the mm-wave antennas in the client device, which implies a high degree of control with multiple antenna elements. Without this level of gain, the handset would be required to transmit high power for each element (+20 dBm or more), which becomes a major battery concern and not a viable solution.

Semiconductor Considerations

The uplink transmitter will be one of the limiting factors in the overall 5G system. In TD-LTE networks today, the power from the uplink transmitter is already an issue, and we expect that the link balance will not improve as we move to higher frequencies.

In battery-operated devices, achieving high power from the transmitter while also achieving adequate linearity can consume huge energy from the battery. The semiconductor process and the amplifier design must both be carefully tailored to reach the best balance of power, efficiency, and linearity.

Today, for mm-wave implementation the contenders are bulk CMOS, SOI, and SiGe. Lower frequencies (below 6 GHz) are likely to use an extension of the GaAs devices used for LTE, but at mm-waves the high number of elements (for higher antenna gain) will create pressure to use a low-cost process.

The cutoff frequency (Ft) of a semiconductor process is often used as metric to compare semiconductor options. In general, for mm-wave RF devices the Ft must be about 5x higher than the operating band in order to achieve reasonable RF performance in an amplifier. CMOS, SOI, and SiGe have now all achieved Ft in the range of 300 GHz, making reasonable performance possible at 60 GHz and high efficiency performance possible at 28 GHz.

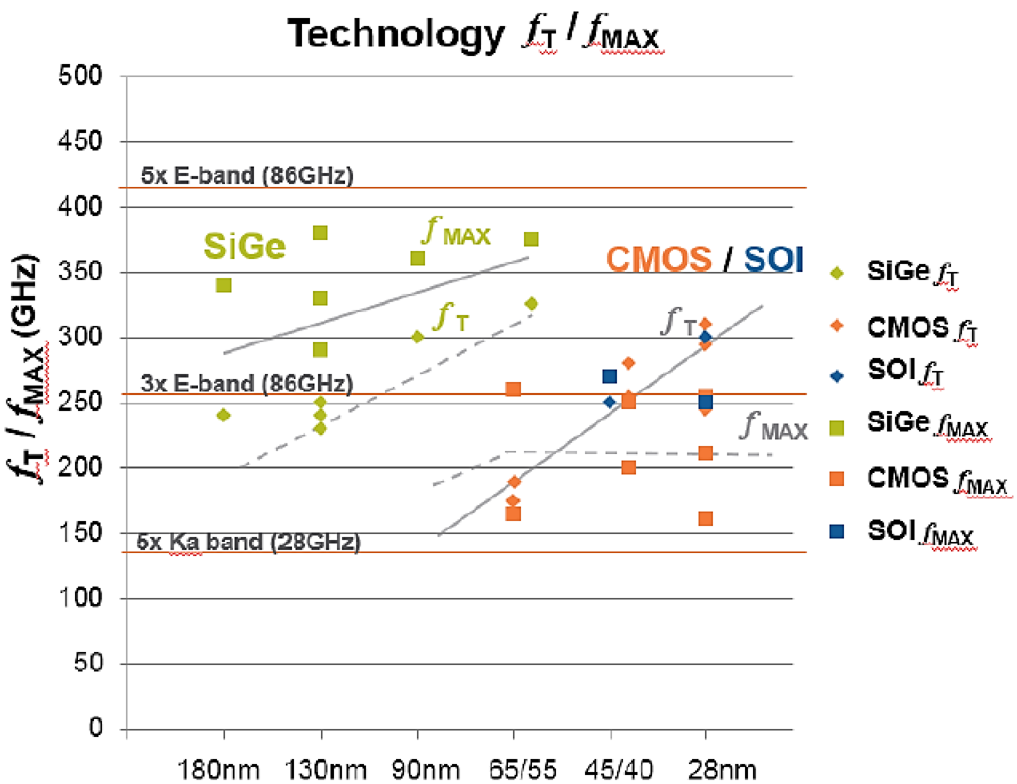

Figure 38. Comparison of Ft and Fmax for CMOS, SOI, and SiGe at various process nodes

Source: GlobalFoundries

Source	Frequency Range	PAE	Saturated Output Power
1	32 GHz	33%	22.4 dBm
2	29 GHz	29%	24.5 dBm
3	42.5 GHz	34%	19.4 dBm
4	46 GHz	42%	22.4 dBm

Figure 39. State-of-the-art for mm-wave SOI amplifier performance

Sources:

1. "MM-wave PAs in 45nm COMS SOI", JH Chen et. Al, IEEE SOI Conference
2. 28 GHz > 250 mW CMOS PA using Multigate-Cell design, JA Jayamon etal, CICS 2015
3. "A 34% PAE, 18.6 dBm 42-45 GHz Stacked PA in 45 nm SOI CMOS", A. Agah et al, IEEE RFIC
4. "High Efficiency Microwave and mm-wave stacked cell CMOS SOI PA" S.R. Helmi et al, TMM 2015

8 COST ESTIMATES

Infrastructure

Base station cost is a hot topic for outdoor 5G network infrastructure. Ignoring the single biggest cost of a 5G deployment (pulling fiber or other backhaul/fronthaul to each site), the hardware cost will be a challenge.

The cost of a Remote Radio Head will certainly be high based on the processing power involved with beamforming and wideband channels….but of course Moore's Law will help along those lines to keep the total RRH cost at a reasonable level.

The more unpredictable part of the cost estimate is in the RF section for 5G Broadband. There's a lot riding on the specifications here :

- If mm-wave ACLR specs are 30 dBc or less, then SOI or SiGe implementation is possible and the RRH/antenna assembly will cost roughly $5,000. This cost level will lead to a compelling ROI for the mobile operators in a mobile 5G scenario (details to follow in our subsequent 5G business case during 2H17)
- If the mm-wave ACLR specs are 45 dBc (similar to the specs at 2 GHz), then more complex radio hardware will be needed. We estimate that the complexity of the RF front end will result in a RRH/antenna unit that costs roughly $10,000. This would most likely result in a marginal business case (to be explored farther in our 2H17 business case scenarios)
- The implementation of Front End Modules at 3.5 GHz and 4.5 GHz will probably result in reasonable RF hardware cost. The ACLR specifications and implementation details are understood better in this frequency range, so overall we're only dealing with the higher cost of multiple antenna elements and T/R modules, not with exotic packaging technology. A 3.5 GHz mMIMO radio head will probably cost about 20% more than today's 8T8R RRH and antenna combination. (In other words, the 3.5 GHz 64T64R unit will have a manufacturing cost in the range of $3,000, compared with about $2,500 for an 8T8R unit today)

Assuming that the specifications come out as planned by major OEMs, the cost of 5G will meet the cost targets we predicted two years ago. The below chart represents our initial view of network costs involved with delivering each GB of data.

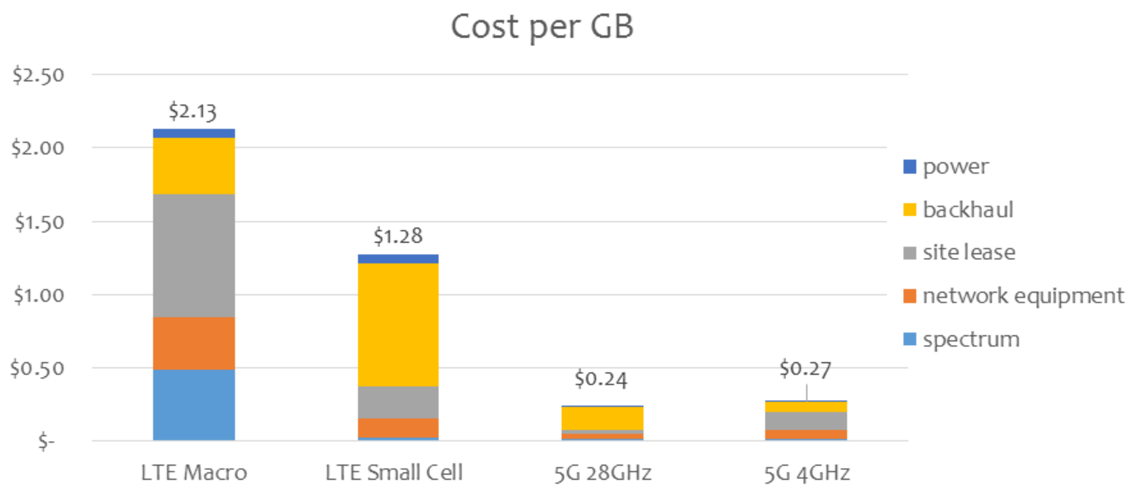

Chart 3: Cost per GB Comparison of LTE and 5G networks, at 4 GHz and 28 GHz

Source: Mobile Experts

CPEs

The fixed CPEs in the US Fixed-Wireless market will be more expensive than similar units for fixed wireless service on MMDS or Wi-Fi. The high-gain antenna and millimeter-wave construction require a higher degree of precision than typical 2-5 GHz gear. In addition, a fixed-wireless 5G CPE will be a dual-band, dual-mode unit because it will use an LTE modem for control channels and a 5G link to aggregate high data speeds. The result is a setup with two modems, two separate transceivers, two RF front ends, plus the complexity of mm-wave steered antennas.

The design of a fixed-broadband CPE is not fully settled yet. We're hearing about indoor units, roof-mounted units, and window-mounted units, with subarrays ranging from 8 elements to 64 elements. The final configuration should be more clear over the next month or so.

Assuming a 16-element array at 28 GHz and a basic LTE Cat-16 modem with 4-5 frequency bands to maximize LTE throughput as well, we estimate that an outdoor CPE will cost roughly $1,000 to manufacture. Certainly this kind of box will be subsidized by the operator so the consumer will not pay that amount for the unit.

Handsets and Tablets

Handsets will be a difficult challenge for 5G above 6 GHz, so we expect most handsets to implement 5G only below 6 GHz, with mm-wave radios only in premium models. For now, we have two cost estimates:

1. A handset or tablet with a "simpler" 5G RF front end below 6 GHz (assuming 4 antennas) is likely to include a few RF components, plus the antennas. The additional BOM cost added to the smartphone will be in the range of

Component	Number per phone	Cost per component
Antenna	4	\$0.10
Bandpass filter—3-6 GHz	4	\$0.30
Switch	1-2	\$0.15
Power Amplifier	1-2	\$0.60
LNA	4	\$0.20
Transceiver	1	\$0.50
5G Modem	1	\$5.00 (additional cost)
		\$8.05 total

Figure 40. Additional BOM cost for 5G in mobile devices, 3-4 GHz

Source: Mobile Experts

2. A handset or tablet with 5G at both 3-6 GHz and 20-40 GHz will become much more costly. The mm-wave radios must be positioned very close to the antennas, and the antennas must be widely spaced on the outside corners of the device because a hand covering one antenna must not be allowed to cover a second antenna array.

   Here's a rough breakdown of the likely BOM costs for a mobile 5G implementation in both frequency ranges:

Component	Number per phone	Cost per component
Antenna	4	\$0.10
Bandpass filter—3-6 GHz	4	\$0.30
Switch	1-2	\$0.15
Power Amplifier	1-2	\$0.60
LNA	4	\$0.20
Transceiver	1	\$0.50
5G Modem	1	\$5.00 (additional cost)
PA/Switch/LNA---28 GHz	8 (4 per module = 32 elements)	\$0.40 per module
Antenna Arrays	4	\$0.50 per array
Transceivers	2	\$1.00 each
Modem	1	\$2.00 (additional cost for higher bandwidth)
		\$17.25 total

Figure 41. Additional BOM cost for 5G in mobile devices, 3-4 GHz and 28 GHz

Source: Mobile Experts

Looking at the cost breakdowns for the two options, it's clear that most 5G tablets or handsets will focus on the sub-6GHz implementation of 5G, along with aggregation of data on LTE. The extra $9-10 to implement mm-wave radio components will most likely be confined to the extreme high end of the market.

9 5G FORECAST

Over the past three years, Mobile Experts has been cautious about our forecast for 5G. The initial fixed-broadband business case was limited to a small part of the globe, and IoT applications simply won't drive investment fast enough.

However, this year we've concluded that mobile operators very dense traffic will have a positive business case. As multiple mobile operators compete in a crowded city like Tokyo, end users will "churn" if they can't get adequate data speed to watch videos on the move. The churn aspect itself is enough to justify investment in 5G for any urban pocket with density higher than about 5 Gbps/km^2. Above this threshold density level, wide bands and massive MIMO are important tools to bring to bear….and 5G is the natural vehicle to use.

Note that LTE can also use mMIMO and can achieve Gigabit speeds. In suburban areas and rural areas where traffic density is light, we do not expect operators to deploy 5G radios right away. For this reason, we are projecting moderate growth, not explosive growth for 5G.

Infrastructure

The 5G infrastructure market will break into three major parts:

- Fixed broadband deployment: This will be addressed with the 5GTF and other pre-5G formats in the USA, but will eventually merge with 5G NR. We have included these radio head shipments in our estimates of mobile 5G infrastructure, because eventually these two applications will merge into a common network.
- High power RRH shipments: Above a power level of +52 dBm, the operator is targeting "macro" level of coverage. Almost all of this high-power deployment will take place below 6 GHz due to the limitations of power in the millimeter-wave bands.
- Low power RRH shipments: Below +52 dBm, the mobile operator will be targeting small coverage areas for each site, so we treat this segment of the 5G market as an extension of the small cell market.

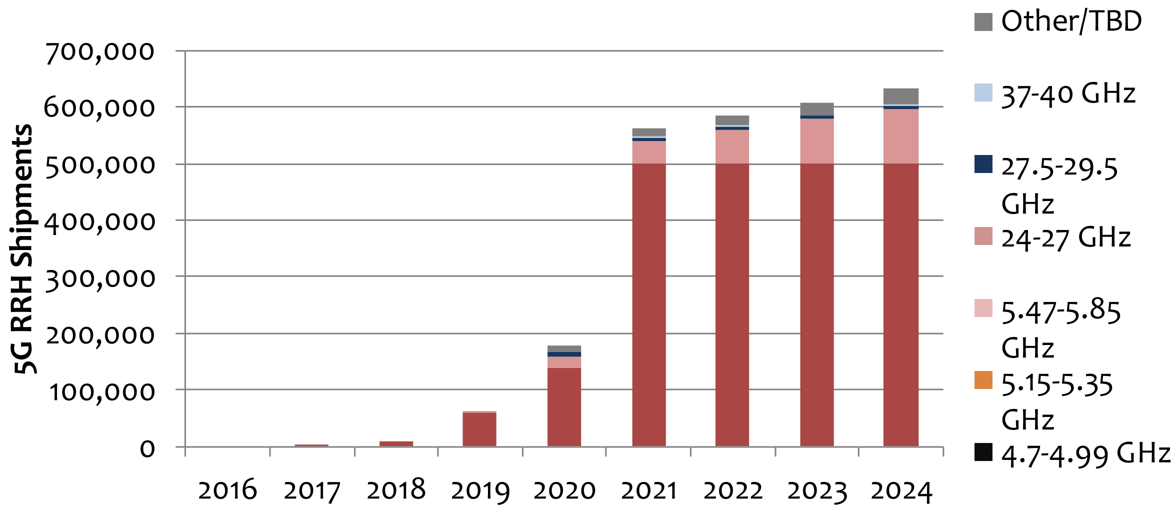

Chart 4: 5G High Power RRH units shipped, by frequency band, 2016-2024

Source: Mobile Experts

The high power 5G infrastructure forecast depends primarily on the Chinese government, and their level of aggressiveness with 5G deployment. China has designated the 3.5 GHz range as its target 5G band, and currently we estimate that a reasonable deployment would consist of roughly 500,000 sectors per year starting in 2021. The rising middle class in China can pay for this level of deployment in the roughly 500,000 urban macro sites across the country.

However, if the Chinese government decides to implement a very aggressive 5G deployment plan, they could deploy 5G on every cell site in the country, roughly tripling our forecast. Chart 5 shows an alternative forecast with aggressive Chinese policy assumptions.

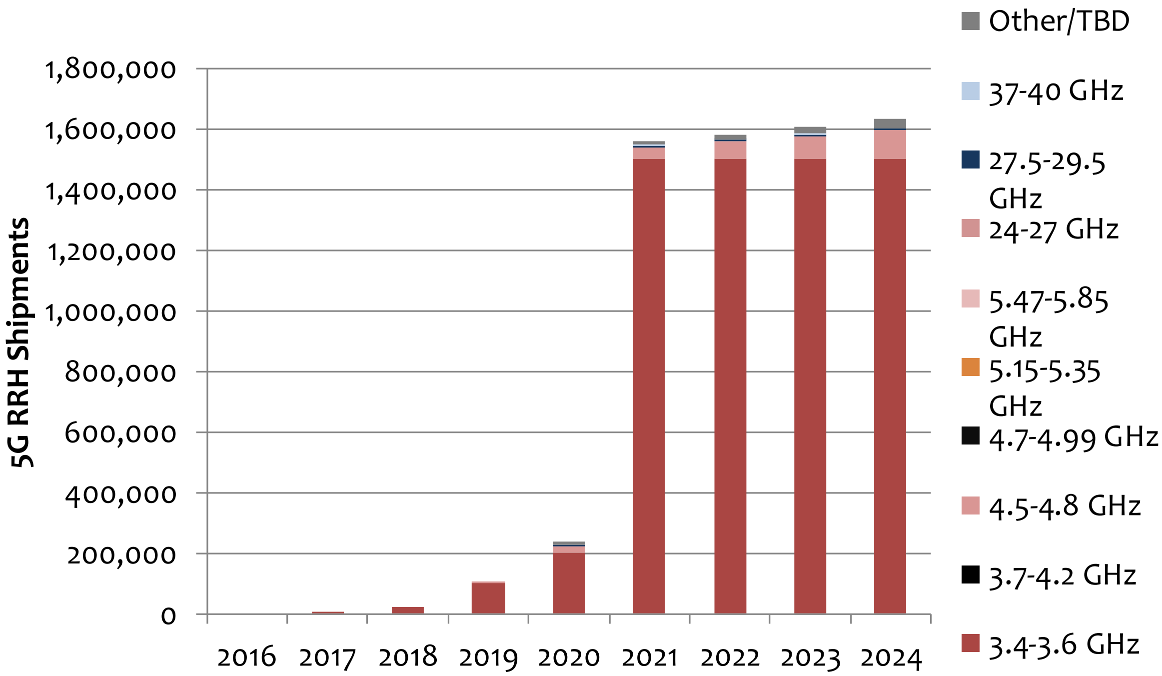

Chart 5: 5G High Power RRH units shipped, aggressive China scenario, by band, 2016-2024

Source: Mobile Experts

Low power RRH shipments will include units below 6 GHz as "small cell densification" for the 5G macro network, and also RRH units in the millimeter-wave bands. While mobile operators want mm-wave equipment with high power transmitters, current amplifier technology is not efficient enough to provide RF power above about +50 dBm.

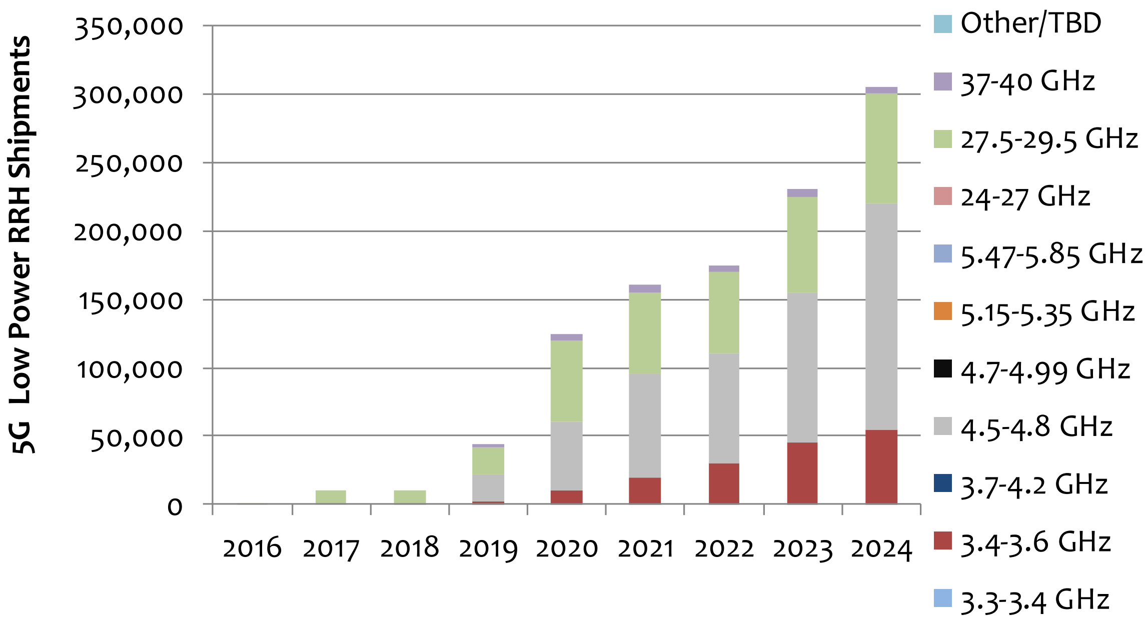

Chart 6: 5G Low Power RRH units shipped, by frequency band, 2016-2024

Source: Mobile Experts

The 5GTF specification will dominate the deployment at 28 GHz, but other forms of a pre-5G standard will start shipping in larger quantity in China during 2018. During 2019, we expect all operators to adopt the 5G NR standard to be released by 3GPP.

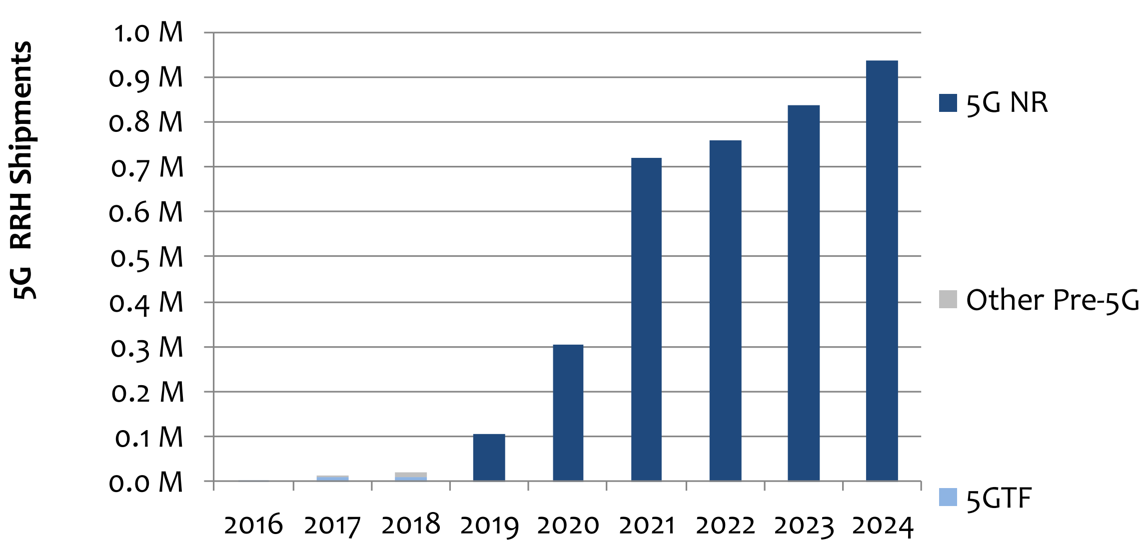

Chart 7: Pre-5G and 5G RRH units shipped, by standard, 2016-2024

Source: Mobile Experts

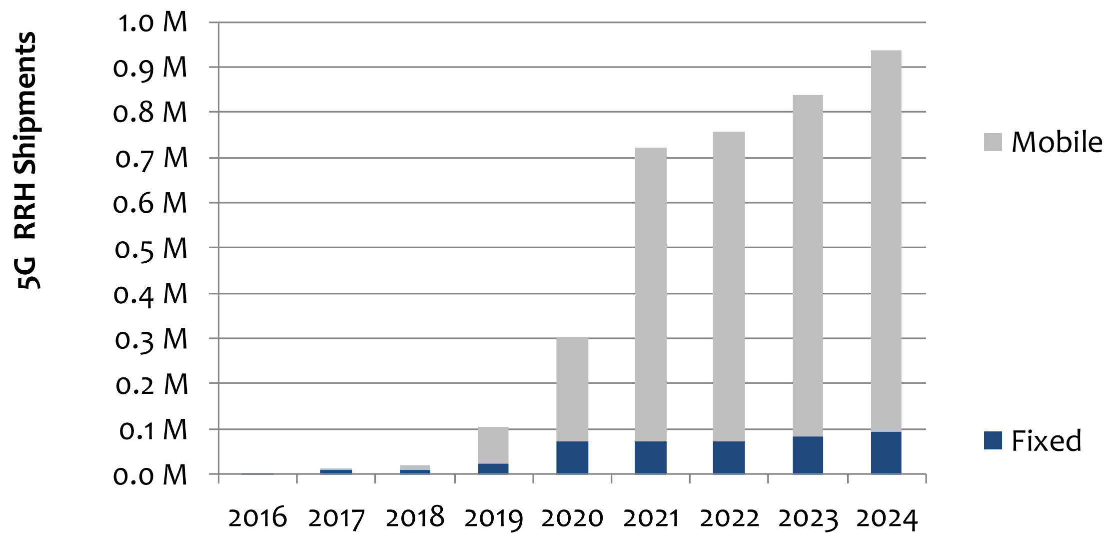

Chart 8: 5G RRH units shipped, by application, 2016-2024

Source: Mobile Experts

CPEs

In the fixed-broadband application, the opportunity is limited. Countries with extensive fiber to the home are not fertile soil for this kind of product, so we don't expect deployment in China, Korea, or Japan. Many European, Latin American, and other Asian countries are still deploying LTE so we don't anticipate a surge of deployment for fixed wireless broadband.

As a result, we project that the US market will have some adoption but that the fixed-broadband opportunity will level off in the 2020 timeframe, as other 5G deployments will be more focused on low-band mobile use cases.

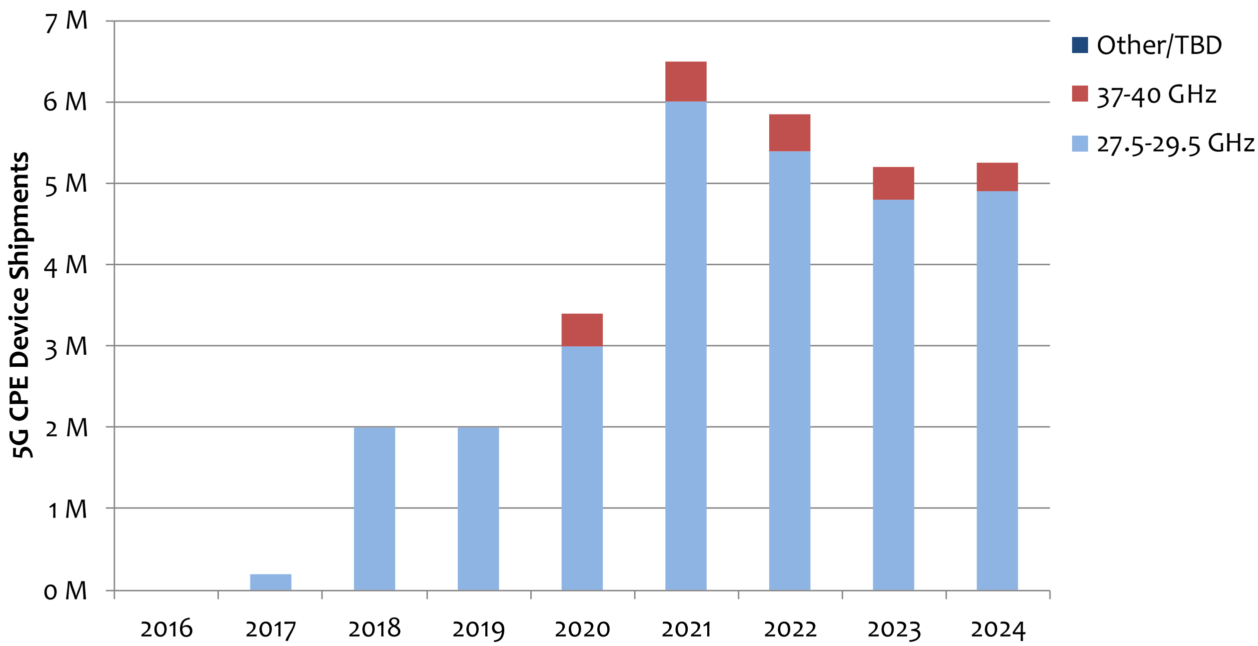

Chart 9: Fixed 5G Broadband CPEs shipped, by frequency band, 2016-2021

Source: Mobile Experts

Handsets and Tablets

China is the big wildcard in the forecast for mobile 5G. China Mobile is making clear plans for a mobile 5G network at 3.5 GHz, and the industry is now scrambling to support it. The question is just how big the deployment will be. If China Mobile follows its pattern from TD-LTE, then millions of radio heads will be deployed at 3.5 GHz, in major dense urban areas as well as lower-density cities. However, if China Mobile follows a purely financial investment scenario, the deployment is likely to be much smaller. Economics dictate that only urban areas justify the 5G investment because high density of revenue is required to pay for the infrastructure. For now, Mobile Experts is forecasting a smaller mobile 5G deployment for China Mobile, spread over 5 years, instead of a surge of millions of sectors per year.

Other major mobile 5G markets such as Korea, Japan, and eventually the USA are more straightforward. Operators in these markets always follow a logical financial decision-making process. In these cases, we project infrastructure coverage that is concentrated in the most dense cities. This network, in turn, will drive 5G adoption in premium handsets but not in every handset.

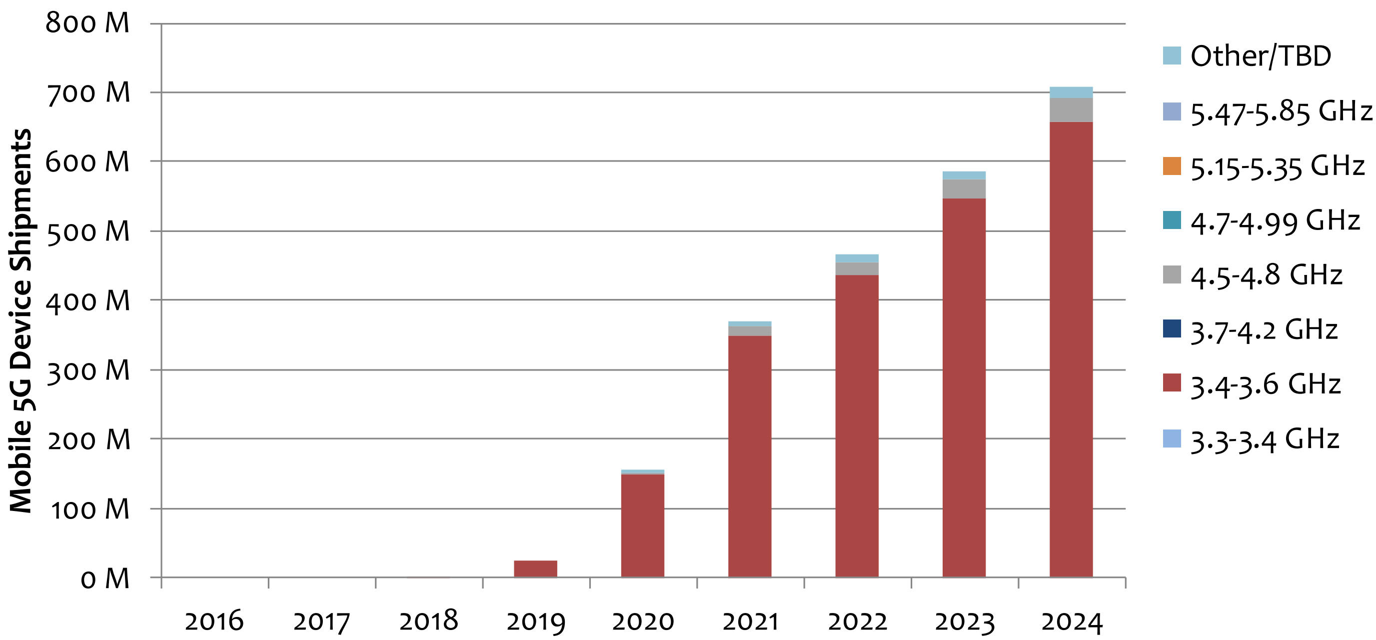

Chart 10: 5G Mobile User Devices, by the main mobile 5G band, 2016-2024

Source: Mobile Experts

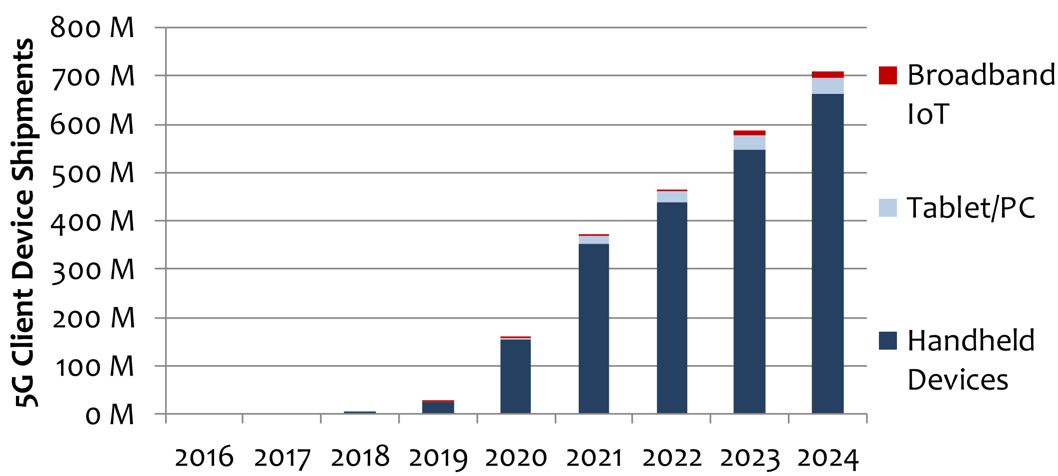

Chart 11: 5G Mobile User Devices, by device type, 2016-2024

Source: Mobile Experts. Not including fixed CPEs

10 COMPANY PROFILES

Ampleon

The power transistor division of NXP spun out in 2015 to become Ampleon. This group is a strong supplier of LDMOS and GaN power transistors for high power RF applications. Ampleon is owned by Jianguang Asset Mgt Co. in China.

Analog Devices

ADI dominates the market for ADCs and DACs in mobile communications, and with their acquisition of Hittite Microwave they have the ability to put together the RF CMOS transceivers and compound semiconductor front end components in heterogeneous assemblies.

Anokiwave

Anokiwave had an early headstart with mm-wave arrays, and has been able to use its extensive experience in radar systems for military applications to realize effective beamforming in the 5G case. Anokiwave is among the first companies to reach production volumes, with significant mm-wave deployment in the field already. The company works with both SOI and SiGe technologies.

Broadcom

Broadcom/Avago has supported millimeter-wave markets for over thirty years, with a strong amplifier capability. The company also has strong filter capability which can apply at 3.5-6 GHz but probably not at mm-wave frequencies. Broadcom is likely to compete in the handset RF front end market in all 5G bands.

Ericsson

At Ericsson, radio technology has always been a strength, and the company comes into the 5G market with deep capability in the integration of the radio, antenna, and baseband processing. Ericsson has also invested heavily in virtualized core networks and Cloud infrastructure to support the mobile applications. Ericsson has a large footprint of 2G-4G base stations worldwide, so they will clearly be a strong player in 5G as well.

GlobalFoundries

GlobalFoundries acquired the IBM fab with strong capabilities for SOI and SiGe technologies. GlobalFoundries now has a partnership with Anokiwave, and offers foundry services to many others in mm-wave radio devices.

Huawei

Huawei is likely to be the dominant supplier for 3.5 GHz 5G systems, with a clear advantage in the Chinese market. The company has already deployed thousands of mMIMO systems at 2.5 GHz for TD-LTE and has a long list of field trials ranging into the mm-wave range as well.

IBM

IBM has partnered with Ericsson to develop a SiGe phased array capability for mm-wave radios, and together the companies have announced their intention to commercialize the technology for the base station mMIMO application.

Infineon

Infineon has strong SiGe capability, and for example has produced a radar-on-a-chip products for automotive applications at 24 GHz and 77 GHz. The company also has a strong position as a supplier of Si LDMOS and GaN power devices. With its recent acquisition of Wolfspeed (CREE), the company has taken a very strong position for the 3.5 GHz 5G radio business.

Intel

For 5G, Intel is focused on antenna/RFFE/transceiver/modem development for the handset, using bulk CMOS to achieve impressive performance. The company has been pushing to capture a more significant chunk of the wireless market for many years, but still the only relevant piece that Intel owns is a share of the baseband modem and transceiver market (which they acquired from Infineon). For Intel, 5G represents an opportunity to use the low power consumption of very-small-geometry bulk CMOS to address beamforming and modem challenges—thus jumping into a leadership position.

M/A-Com

M/A-Com provides custom MMIC fabrication and assemblies, and has long experience with millimeter-wave antenna arrays and transceiver elements.

Microsemi

Microsemi produces integrated single-function modules using SiC, SiGe, GaAs, GaN, and InP, with capabilities up to 140 GHz.

Nokia

As a major base station supplier, Nokia has already deployed more than 500 RRH/antenna units in the field at 28 GHz, and is well on its way to supporting multiple products ranging from 3.5 GHz through 39 GHz. Nokia has acquired Alcatel-Lucent, and by combining these two companies they have aggregated a huge installed base of 2G-4G base stations that they can use to add 5G network deployments.

Nuvotronics

Nuvotronics constructs steerable antenna arrays for military (radar) applications, and has experience with the integration of antennas, filters, power amplifiers, LNAs, and back-end processing in heterogeneous assemblies.

NXP/Freescale

NXP recently acquired Freescale, which has been actively working to develop integrated modules for automotive radar applications at 77 GHz. NXP is developing high power transistors using GaN (as well as their legacy Silicon LDMOS products) which will be used in 3.5 GHz and other sub-6 GHz radio head deployment.

Qorvo

Qorvo supplies GaN devices and several other compound semiconductor MMICs, with clear experience in both government and commercial markets. Qorvo is working with multiple OEMs on mm-wave 5G prototyping, using GaN devices.

Qualcomm

Through its acquisition of Wilocity, Qualcomm has become the leader in development and shipments for WiGig radios at 60 GHz. Over the last year, Qualcomm has advanced the use of RFCMOS for radios and RF front ends at 28 GHz using advanced beamforming technology.

Samsung

Samsung is trying to use 5G to break into the mobile infrastructure market, and has invested heavily in the network infrastructure area. Samsung has performed some of the most impressive field trials related to non-line-of-sight links at long distance at 28 GHz, as well as mobile 5G testing at speeds up to 100 km/hour.

Skyworks

Skyworks is developing RF-SOI devices for mm-wave communications applications, and also has extensive shipment history with millions of SiGe BiCMOS devices.

Sumitomo

Sumitomo is a leading supplier of power transistors using GaN material for 3G/4G base stations, and the company has experience with Wafer Level Chip Size Packaging (flip-chip mounting of one die on top of another die), with 80 GHz LNAs. Sumitomo is currently the leading supplier of power devices for the 2.5 GHz Massive MIMO deployment in TD-LTE.

Wolfspeed (CREE)

Infineon had agreed to acquire Wolfspeed from CREE, but the deal fell apart recently due to pressure from the US government (they didn't want a German company to buy an American company). Wolfspeed is the #2 supplier of GaN power devices on the mobile infrastructure market, and will continue in the LTE market. 5G plans are in transition, but Wolfspeed can be expected to take a major role in 3.5 GHz deployment.

ZTE

ZTE has been developing some interesting technology to estimate the mMIMO channel conditions in FDD mode where the uplink and downlink are very different. The company should not be discounted. ZTE is in a good position to capture major 5G market share with Chinese deployment leading the market in the 2019-2021 timeframe. The company is actively developing a 3.5 GHz radio/antenna solution today.

11 METHODOLOGY

For our 5G analysis, we are investigating the technology first, using a logical, analytical process. We interviewed more than 30 mobile operators with regard to 5G plans, including:

- ***Why*** will the operator deploy 5G infrastructure? What is the likely business case and does 5G make sense financially?
- What will the operator deploy to satisfy the business case?
- What requirements will be imposed by regulatory agencies and competitive pressures?
- What conclusions can we draw from the requirements based on the state-of-the-art in semiconductor performance?

The first step was completed in 2015, with a generally favorable view of WHY operators will invest in 5G under clear business case scenarios. In 2016, we filled in some cost estimates for a 28 GHz deployment for fixed broadband. We added cash-flow analysis of the 5G fixed broadband business case, to determine how widely the fixed deployment would be pursued by mobile operators.

This year, we focus on mobile 5G. The standards bodies have reached a level of consensus on technology, and we see specific plans coming together for 5G deployment in mobile bands below 6 GHz. This report brings together input from more than 30 operators, from every major OEM and other participants in the 3GPP study groups, and multiple follow-up interviews to test each company's claims.

The semiconductor implementation we describe in this report is based on interviews with about 30 semiconductor and component vendors. In each case, we interviewed these players to determine the technology limits and the cost implications of various packaging and integration alternatives.

The next step in Mobile Experts 5G research will be to complete the cash-flow analysis for the mobile 5G investment case. We intend to focus on dual-band 5G networks, with coverage in the 3.5 or 4.5 GHz bands, and a capacity layer at about 20-30 GHz.

12 APPENDIX: EXAMPLES OF MMIMO AND 5G DEMO HARDWARE

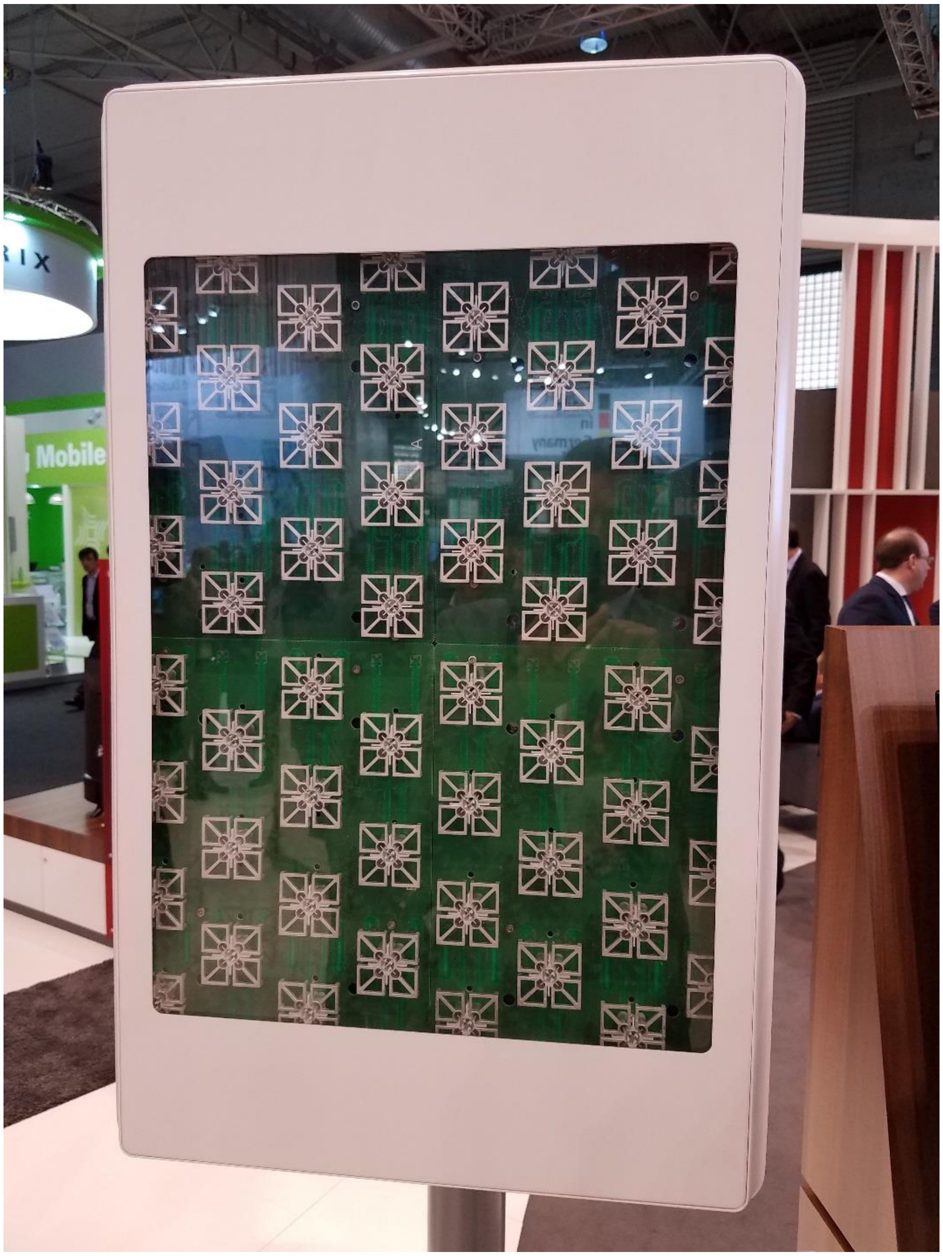

Figure 42. Huawei 2.6 GHz TD-LTE mMIMO array (commercial trial with Vodafone)

Source: Mobile Experts (MWC 2017 photo)

Figure 43. Huawei 2.6 GHz TD-LTE mMIMO array (commercial trial with Vodafone)

Source: Mobile Experts (MWC 2017 photo)

Figure 44. Samsung RRH at 28 GHz

Source: Mobile Experts (MWC 2017 photo)

Figure 45. Samsung mMIMO array, unknown frequency band (field trial with Korea Telecom)

Source: Mobile Experts (MWC 2017 photo)

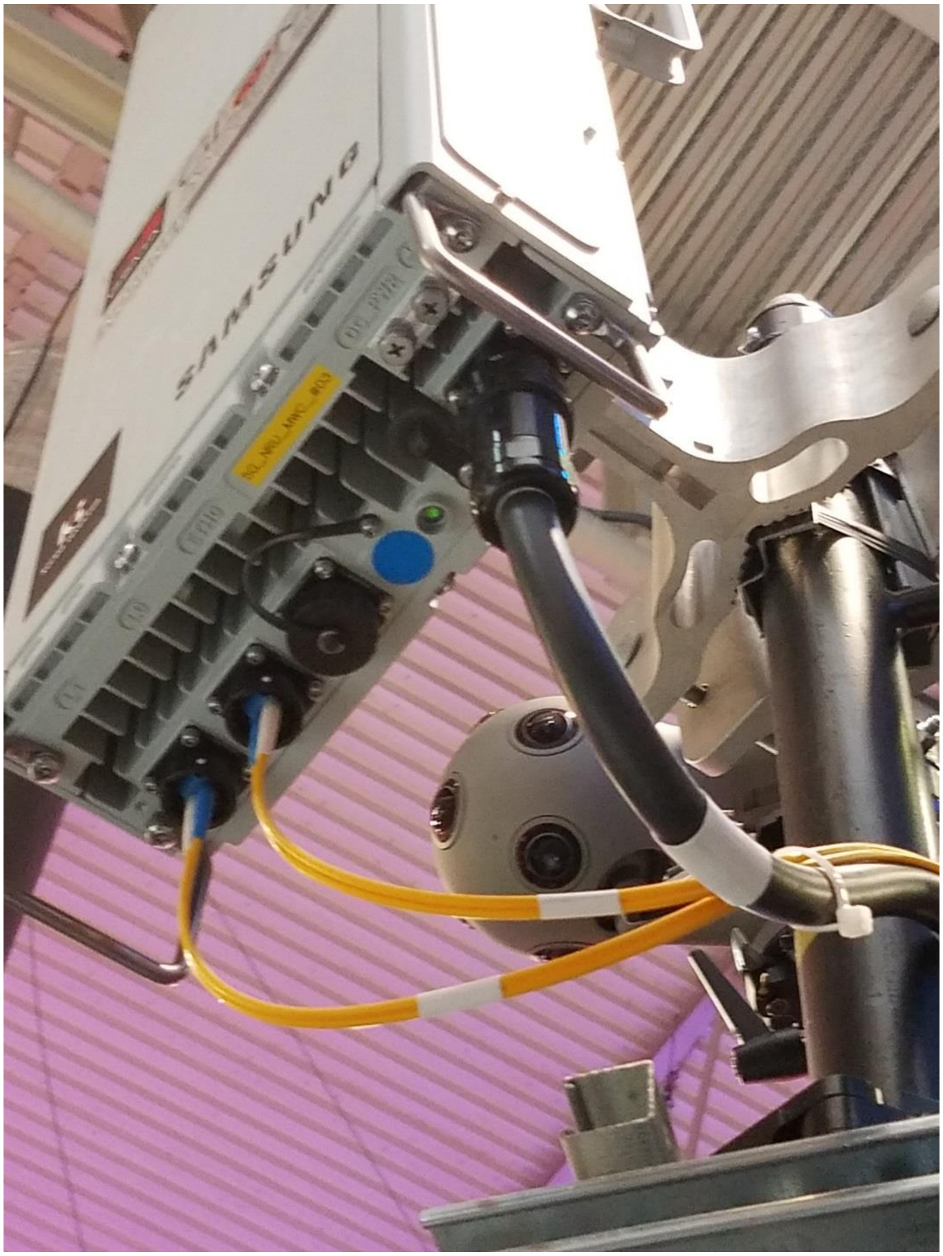

Figure 46. Samsung mMIMO array, bottom side (field trial with Korea Telecom)

Source: Mobile Experts (MWC 2017 photo)

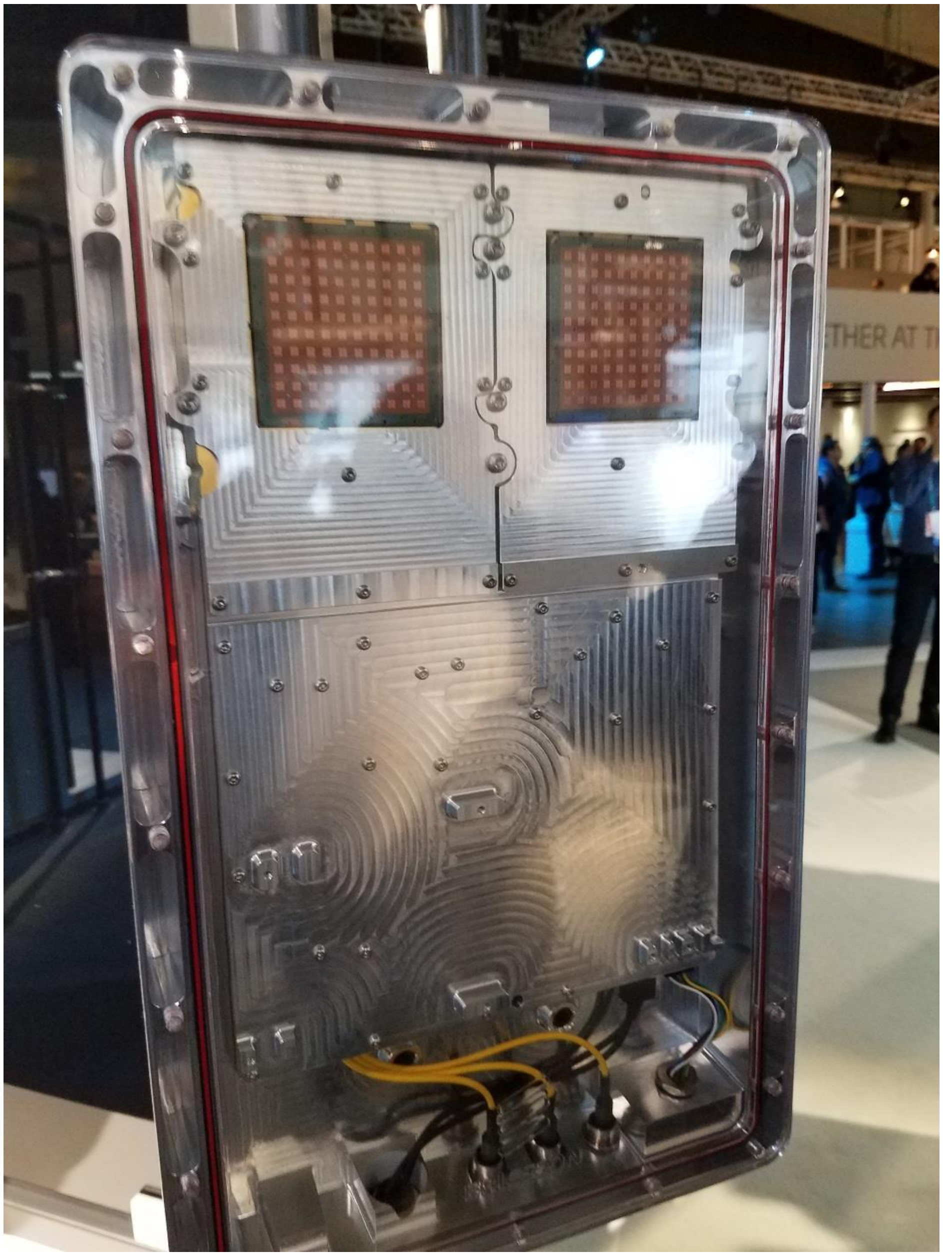

Figure 47.   Ericsson high power mMIMO array, 28 GHz (field trial with Verizon)

Source: Mobile Experts (MWC 2017 photo)

Figure 48.   Ericsson high power mMIMO array, 28 GHz (back side)

Source: Mobile Experts (MWC 2017 photo)

Figure 49. Intel CPE at 28 GHz (field trial with Verizon)

Source: Mobile Experts (MWC 2017 photo)